NASA Contractor Report 163114

SPF/DB Primary Structure For Supersonic Aircraft (T-38 Horizontal Stabilizer)

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Los Angeles, California 90009

CONTRACT NAS4-2651
DECEMBER 1981

NASA
National Aeronautics and
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Dryden Flight Research Facility
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FOREWORD

This final report documents the effort completed by Rockwell International, North American Aircraft Division (NAAD) under National Aeronautics and Space Administration (NASA) Hugh L. Dryden Flight Research Center contract No. NAS4-2651 for a period of performance from April 1979 through October 1981. The program was conducted for the purpose of utilizing the superplastic forming and diffusion bonding process on a primary structure for a supersonic aircraft.

This program was administered under the technical direction of Mr. Berwin Kock, project manager of the NASA Dryden Flight Research Facility, Ames Research Center, California. The Rockwell program manager was Mr. Rene Rivas. Supporting Mr. Rivas and their areas for responsibility were:

Mr. D. Schulz - Material and Producibility
Mr. L. Israeli - Structural Analysis
Mr. G. Rainville - Structural Design
Mr. F. Abdi - Finite Element Modeling

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SPF/DB PRIMARY STRUCTURE FOR SUPERSONIC AIRCRAFT

(T-38 HORIZONTAL STABILIZER)

BY ALFREDO R. DEL MUNDO, FRED T. MC QUILKIN, AND RENE' R. RIVAS

NORTH AMERICAN AIRCRAFT OPERATIONS OF ROCKWELL INTERNATIONAL

1.0 SUMMARY

The North American Aircraft Division (NAAD) of Rockwell International (Rockwell) under contract to NASA Dryden Research Facility, Ames Research Center, conducted this program to demonstrate the structural integrity and potential cost savings of superplastic forming/diffusion bonding (SPF/DB) titanium structure for future Supersonic Cruise Research (SCR) and military aircraft primary structure applications.

NAAD designed the SPF/DB T-38 horizontal stabilizer replacement to satisfy the design criteria and requirements of the existing T-38 horizontal stabilizer. Design criteria were supplied by the Northrop Corporation Aircraft Group as part of a subcontract agreement.

The general concept of using a full-depth sandwich structure which is attached to a steel spindle, was retained. This concept was necessary because of the form, fit, and function requirements of the SPF/DB horizontal into an existing T-38 airframe inhibited some of the more desirable concepts because of the necessity of using a steel spindle. Complete design freedom was also inhibited because of the desirability of retaining original T-38 stiffness and weight distributions as in the original tail to retain original flying qualities and flutter boundaries of the airplane.

Within these constraints, two basic design concepts were evaluated - the spindle attachment and the SPF/DB sandwich core configurations. The sandwich core configurations considered were dimple core, straight truss core, and sine wave truss core using three- and four-sheet technologies. Several spindle and spindle attachment design concepts were evaluated. Some concepts used the existing spindle with minor modifications, while others required a new design.

Trade studies demonstrated that the optimum design should employ double-truss, sine wave core in the deepest section of the surface, making a transition to single-truss core in the thinner areas at the leading and trailing edges and at the tip. At the extreme thin edges of the surface, the single-truss core was changed to dot core to provide for gas passages during the SPF/DB process.

The selected SPF/DB horizontal stabilizer design consisted of a one-piece SPF/DB sine wave truss core panel, a trunnion fitting, and reinforcing straps. The fitting and the straps were mechanically fastened to the SPF/DB panel (figure 1-1).

The program produced a number of innovations which will improve the efficiency of all future SPF/DB titanium structure. These included:

1. Development of a method of producing sine wave, truss core which transitions from double to single truss

2. Development of a detail NASTRAN analysis for sine wave, double-truss core sandwich

3. Determination of the effect of various core parameters on structural properties

4. Application of single-cycle SPF/DB processing to double-contour surfaces such as the horizontal stabilizer

5. Feasibility of expanding a four-sheet sandwich structure to a depth of 3-1/2 inches

The results of this program, coupled with spinoff from a concurrent IR&D program which produced and tested four-sheet sandwich (including sine wave, double-truss core), indicate that additional development and testing are required for a deep double-truss sandwich over 38 mm (1.5 inches) before SPF/DB structure is ready for application to full-scale primary structure. This program therefore developed unique design concepts, produced detail design drawings, finite-element analysis, structural analysis, feasibility demonstration, and test data for representative structural panels in 710 by 710 mm (28- by 28-inch) panel sizes. Relatively low structural allowables achieved with the original four-sheet sandwich and the difficulty in producing this thin core-sheet configuration required additional effort to resolve potential risk problems associated with fabricating the original design. Solutions to these problems were identified; however, the additional effort required to validate these solutions and complete the program were beyond the scope of the contract.

This report documents the accomplishments achieved during the first two phases of the program, including preliminary design and development and detail design. The third phase, fabrication of the full-scale article, was not completed.

2.0 INTRODUCTION

NASA has been conducting a supersonic cruise research (SCR) program to develop a strong technology base to support rational decisions concerning the development of future supersonic aircraft structure. One area of interest for SCR is the development of superplastic forming and diffusion bonding (SPF/DB) of titanium. This process is capable of diffusion bonding sheets of titanium material to each other in selected areas by applying heat and pressure. After completion of the bonding process, gas is injected between the titanium sheets, expanding the part until it fills a shaped-tool cavity. Titanium is capable of extremely large strains prior to failure if proper temperature and strain rates are applied. This process will form a monolithic titanium-sandwich panel with integrally diffusion-bonded core. Exploitation of this advanced structures technology, explained in detail in appendix A, can substantially reduce the cost and improve the efficiency of conventional high-temperature structure.

Rockwell was contracted to conduct a program to design, build, and test SPF/DB T-38 horizontal stabilizers. The primary objective of this program was to demonstrate the structural integrity and potential cost savings of SPF/DB titanium for future SCR and military aircraft primary structure applications. A secondary objective was to provide a direct cost/weight comparison between full-depth aluminum honeycomb structure and SPF/DB titanium technology. A full-scale horizontal stabilizer assembly for a T-38 supersonic trainer was to be designed, fabricated, static tested, and flight demonstrated to accomplish this objective. The T-38 horizontal stabilizer was specified as the demonstration article for two reasons: (1) NASA's T-38 aircraft were available for flight testing the redesigned components, and (2) the existing stabilizers were experiencing corrosion problems which would be eliminated by the substitution of a titanium structure.

This 28-month program was originally structured into three technical tasks, as shown in figure 2-1, and two reporting tasks. The technical tasks were task 1, Preliminary Design; task 2, Development and Detail Design; and task 3, Concept Evaluation. The culmination of these tasks was the fabrication of a left and right horizontal tails for the T-38 aircraft to be flight qualified through test and analytical efforts. Tasks 4 and 5 consisted of periodic reporting and delivery of data at the end of the program.

2.1 TASK 1 - PRELIMINARY DESIGN

This task was a 3-month effort in which design criteria necessary to ensure form, fit, and function of the horizontal stabilizers were collected.

Northrop Corporation, as a subcontractor to Rockwell, supplied all criteria, drawings, and interface requirements necessary to fabricate the T-38 titanium SPF/DB horizontal stabilizer and meet all form, fit, and function requirements of an existing T-38 airplane. Design criteria were identical to the aluminum honeycomb design, including weight distribution, stiffness, and strength requirements in order not to affect the flutter and flying quality of the T-38 airplane.

Trade studies were performed on various design concepts in order to select the design which would meet design criteria with minimum cost and weight. Layouts were developed with sufficient detail to allow structural, producibility, mass properties, and cost analysis to be conducted.

Preliminary stress analyses of the candidate concepts were performed in order to assure that structural integrity and all design criteria were met. The stabilizer panel skin and core were checked for strength, general stability, and local crippling. Spindle fitting concepts were also stress checked to assure that the induced joint loads due to combined applied moment, torque, and shear loads could be counteracted.

As a result of the trade studies, a preferred concept was selected for detail design, fabrication, and test during the subsequent program tasks. The design analysis assured that the selected configuration met the requirements for static strength, stiffness, durability, and acoustic fatigue. A report delineating the preliminary design effort and the rationale for the configuration selection was submitted to NASA at the end of this task.

Subsequent to the selection of the final SPF/DB horizontal stabilizer configuration, NAAD prepared a design development test plan which defined tests necessary to validate critical areas of the selected preliminary design concept. This plan included test specimen configuration, test methodology, instrumentation, and data acquisition requirements. Planned development tests included bending beams, core shear and compression specimens, and a joint verification specimen.

2.2 TASK 2 - DEVELOPMENT AND DETAIL DESIGN

The detailed drawings required for the program were prepared during this task. These drawings included the tool design required to support the test program and the full-scale horizontal stabilizer fabrication. A manufacturing flow plan and manufacturing process procedures were also prepared for use during full-scale fabrication.

This task detailed fabrication and testing of the specimen identified in the development test plan during task 1. The test program included bending beam and core shear specimens cut from 710 by 710 mm (28- by 28-inch) panels and a joint development test duplicating the spindle-to-panel structural joint. Tooling for the joint development test was fabricated during this task.

The predicted allowables used to design the stabilizer were based on extrapolations of conventional three-sheet technology analysis. However, a concurrent IR&D program, Truss Core Sandwich Structure Verification, in which four-sheet truss core panels were fabricated and tested, revealed that design parameters and structural allowables used in the horizontal stabilizer design were excessively optimistic. These data were confirmed when a NASTRAN model was constructed to allow a detailed analysis of the proposed sandwich design. Although the IR&D program showed promise in the ability to expand core in thin gages and depths required in 710 by 710 mm (28- by 28-inch) panel sizes, the processing required would have been difficult to achieve in a large-scale structure and would have been an undue risk to successful completion of the T-38 program. This conclusion, and the low structural core properties achieved, resulted in a decision that core design concept should be revised to increase the core gages, both to raise design allowables (even though the allowables achieved in the test program were marginally sufficient to achieve the required strength), as well as to reduce significantly the manufacturing risk. The increased core gages, combined with a transition to a single-sheet truss core design around the periphery of the stabilizer, kept the weight to the original design targets. Transiting from a four-sheet to a three-sheet sandwich was proven feasible by the construction of a producibility test specimen which was successfully fabricated.

Results of these tests and analyses came too late to influence the original design, so that a redesign and analysis was required to incorporate these changes. Additionally, more structural tests were required to confirm the structural allowables of the new four-sheet core as well as transition area. This was beyond the cost constraints of the program, and the program was stopped at this point with completion of tasks 1 and 2. It was concluded at this point that the recommended design changes would have resulted in a successful structural demonstration article from 710 by 170 mm (28- by 28-inch) panels to the full-size horizontal stabilizer. The recommended changes, however, were partially made to reduce this risk so that the scaleup risk would also have been minimal. However, NASA decided not to pursue planned development testing and fabrication of the full-scale stabilizer, defined in task 3, because of the additional scope and effort required.

2.3 TASK 3 - CONCEPT VALIDATION

The fabrication of a full-scale stabilizer tool proof article to be used as a process verification part (PVP) was planned for this task. Quality assurance inspection criteria were to be applied to the component. Qualification tests conducted on coupons, elements, and subcomponents cut from the PVP were to be performed. At the conclusion of test activities, a summary qualification test report was to be prepared and submitted to the customer for approval.

After completion of the process verification part, four SPF/DB titanium stabilizers were to be fabricated. One horizontal stabilizer was to be static tested by Northrop as part of the subcontract. Two of the stabilizers were to be assembled for flight test at NASA's Dryden Research Center, while the fifth part was to be retained as a spare part.

The Government was to conduct a ground vibration test (GVT) to determine flutter characteristics prior to flight test. The data generated by the GVT were to be analyzed by Northrop prior to the flight test.

This report describes the work accomplished during the contracted tasks of this program, which resulted in a reevaluation of the status of four-sheet truss core SPF/DB sandwich.

3.0 PROGRAM ACCOMPLISHMENTS

This section describes the technical effort made on this program. The technical program, the problems encountered, and their eventual resolution during the course of this program have provided a significant contribution to the SPF/DB technology data bank that will aid both in future research and applications.

3.1 TASK-1 - PRELIMINARY DESIGN

3.1.1 DESIGN CRITERIA

The T-38 SPF/DB horizontal stabilizer design was developed to meet the design criteria of the existing stabilizer. Design data were supplied by Northrop Corporation Aircraft Group as part of a subcontract agreement.

Geometric data received from Northrop included the basic airfoil planform shape and stabilizer reference stations. Figures 3-1 and 3-2 show typical geometric data for the stabilizer. The new SPF/DB horizontal stabilizer was designed to match the outside mold line of the baseline design, and the root rib area was sized to prevent interference with the fuselage during stabilizer actuation.

Two critical loading conditions established the structural limits of the stabilizer. These conditions set the ultimate loads for bending moment, torque, and vertical shear. The supersonic loading condition shown in figure 3-3 occurs at mach 1.63 at 6,550 meters (21,500 feet) and $N_z = 1.00$. The subsonic condition shown in figure 3-4 occurs at mach 0.95 at 6,550 meters (21,500 feet) and $N_z = 6.50$. A dynamic pressure distribution was also given for various stations along the stabilizer percent chords as shown in figure 3-5. These pressures correspond to the supersonic loading condition.

The stiffness criteria for the stabilizer panel were expressed in terms of bending and torsional stiffness (EI and GJ) along the stabilizer from root rib outboard to the tip rib. The EI and GJ values reach their maximum near stabilizer station 27.7 and decrease until near zero at the tip rib. The EI and GJ values represent the actual stiffness of the baseline horizontal and are shown in figure 3-6.

The advantage of substituting titanium alloy for the baseline aluminum alloy is evident since the required stiffness (EI and GJ) was held constant, but the E and G value of titanium are higher than aluminum. Therefore, the required I and J values are reduced for the SPF/DB stabilizer by the modulus of elasticity and shear modulus ratios of the two materials.

3.1.2 TRADE STUDIES

T-38 horizontal stabilizer trade studies considered two basic design problems, the spindle and SPF/DB sandwich core areas. The core designs considered were dimple, truss, and sine wave configurations using both three- and four-sheet technologies. Some of the spindle concepts used the existing Northrop rough forging with and without welding, while others required a new hand forging.

Two potential paths for carrying airloads into the spindle were considered. In one, a center spar was installed in the panel, with the core running chordwise to intersect the spar. Shear loads from the core were then transferred to the spar which carried the load inboard through the spindle.

The second load path concept did not contain a center spar. The core ran spanwise, dumping shear loads into a heavy root rib. Skin doublers were located at the spindle fitting, where all shear and bending loads were transferred from the panel to the spindle fitting through several large bolts.

3.1.2.1 Core Evaluation

Three basic core configurations, each with both single truss and double truss, were reviewed (figures 3-7 through 3-9). The comparison is shown in table 3-I in terms of titanium thickness and weight per unit area. These data, obtained from calculations based on loads in the region of the midroot chord, indicated that double sine wave and double-dimple core are the most efficient configurations.

Although the double-truss design was shown to be slightly heavier than the double-dimple core design, it was selected because of the limited data base for dimple core analysis.

3.1.2.2 Spindle Attachment

The critical portion of the stabilizer design is the spindle fitting attachment joint. This joint involves the transfer of very high loads from the stabilizer to the spindle fitting. The Northrop design bonded a spar into the aluminum honeycomb assembly and mechanically fastened the spar to the skins. A similar approach is not recommended in an SPF/DB design because of fitup and shimming requirements. Trade studies were conducted to determine the optimum method of attaching the steel spindle to the stabilizer using the existing Northrop forging.

Concept A - Figure 3-10

The existing forging is machined to fit inside the SPF/DB panel and then fastened with a 4.76 mm (0.1875 inch) blind bolts. An integral titanium spar runs from the outboard end of the spindle fitting to the tip rib.

Concept B - Figure 3-11

An extension is welded to the existing forging, making it symmetrical about the spindle centerline. The 12.7 mm (1.50 inches) diameter, 1.813 Pascals (125 ksi) bolts are installed through the upper and lower skins. Separate fasteners are used in the top and bottom surfaces to prevent preloading of the fitting. The effectiveness of the fasteners located near the fore and aft limits of the fitting will require testing prior to full-scale demonstration.

Concept I - Figure 3-12

Machined titanium blocks are preplaced in the SPF/DB tool. These blocks are then secondary diffusion bonded to the face sheets during the SPF/DB cycle.

Concept II - Figure 3-13

A solid, machined titanium block is diffusion bonded to the panel as in concept I. However, the steel fitting extends further outboard to accommodate four 9.52 mm (0.375 inch) blind fasteners. The major fasteners are 14.287 mm (0.562 inch) diameter to improve fastener spacing over concept I.

Concept III - Figure 3-14

The spindle forging is machined to provide a transition into a solid block, which is inserted between the face sheets of the SPF/DB panel. Doublers increase the face sheet thickness to 10.16 mm (0.400 inch) at the fasteners. This design requires a bump in the mold line because of the thick face sheets, in addition to a fairing over the fastener heads and nuts. The inside surfaces of the face sheets require light machining or shimming to ensure proper fitup.

Concept IV - Figure 3-15

A double-shear fitting was designed from the existing forging. Three 19.05 mm (0.750 inch) diameter bolts are used to transfer the load, and a fairing similar to concept III would be required to cover the bolts.

Concept V - Figure 3-16

This design is a modification of concept III. An extension is welded to the existing forging to allow the placement of the three bolts in a symmetrical pattern around the centerline of the spindle. This design ensures a more uniform loading of the fasteners. The root rib is spliced to the fitting with tabs and blind fasteners.

Concept VI - Figure 3-17

This spindle design fits over the SPF/DB panel and is then fastened with three 19.05 mm (0.750 inch) diameter bolts. A new forging would have to be produced for this design because of the additional size required. This design allows the root rib to be continuous, a desirable feature.

Concept VII - Figure 3-18

This design is similar to concept V except that it has been modified to accommodate a continuous root rib. A shear tie between the spindle fitting and the root rib is made by installing 6.35 mm (0.250 inch) blind bolts as shown in section E-E.

Concept VIII - Figure 3-18.

This design uses the existing Northrop spindle forging, machined in the shape of an I-beam. The I-beam extends from horizontal stabilizer station (HSS) 27.70 to 43.0. The stabilizer panel is formed with an integral beam running down the 62.7-percent plane.

A summary of the spindle trade study with a listing of advantages and disadvantages of each concept is presented in table 3-II.

3.1.2.3 Selected Concept

The selected core design for the stabilizer panel was a double sine wave configuration with the bond nodes running in the chordwise direction. Double-dimple core is specified along the outer 50 mm (2 inches) of the leading edge, tip rib, and trailing edge, to be used as an integral gas manifold which would feed the individual truss chambers.

After the stabilizer panel is formed, a slot is cut in the panel to accommodate the center web of the I-beam. The stabilizer is assembled by sliding the machined I-beam over the panel as shown in section A-A (figure 3-19), shimming to fit, and then installing blind fasteners along the spar caps. The fasteners at the outboard end of the I-beam will splice the outboard steel strap to the I-beam, as shown in section B-B (figure 3-19), creating a continuous load path which gradually picks up panel loads and feeds them into the spindle fitting. Outboard station 43.0 steel straps are mechanically fastened to the upper and lower face sheets, as shown in section C-C, to act as spar caps.

Concept VIII was selected as the preferred T-38 horizontal stabilizer concept because of its advantages over all other design concepts considered. This concept uses the existing spindle forging without the need for adding material by welding on extensions. This design provides a direct load path into the spindle which continuously picks up the loads along the length of the stabilizer without requiring heavy skin doublers. This concept also meets strength requirements and remains within mold line constraints.

3.1.3 DEVELOPMENT TEST PLAN

A test program was established to support the full-scale fabrication of the T-38 horizontal stabilizer. This development program was initiated immediately after preliminary design review and was designed to verify the core properties and local instability values of deep, double sine wave sandwich core. Test data would define the strength and stiffness characteristics of the structure under the stabilizer loading conditions. The test plan is shown in table 3-III.

The four types of specimen tests which were planned for the program are shown in figure 3-20. The bending beams were potted at both ends to prevent crushing of the core during test. The face sheets of the flatwise compression specimens were coated with a resin compound, then machined flat and true. Core shear specimens were loaded by means of steel loading plates bonded to the face sheets.

The joint development task was a complex manufacturing feasibility and stress check of the steel spindle-to-panel joint. The specimen consists of a steel cantilever beam assembly fixed to the test support structure with eight tension bolts. The steel assembly is machined into an I-beam which is assembled over the panel and then fastened with blind bolts. Steel straps joggle under the beams at the end of the steel spindle to form a splice joint. The straps then run outboard beyond the panel and are used as loading structure. Four weld assemblies are fastened along the periphery of the panel to introduce vertical shear and moment loads which simulate the actual stabilizer loading.

3.2 TASK II - DEVELOPMENT AND DETAIL DESIGN

3.2.1 DETAIL DESIGN

The SPF/DB horizontal stabilizer replacement (figure 3-21 (ref D707-701)) was designed to satisfy all design criteria of the existing aluminum horizontal stabilizer shown in figure 3-22.

The SPF/DB design employs a four-sheet technology using the selected double sine wave core configuration. It consists of the horizontal stabilizer panel, trunnion fitting, and straps. The one-piece SPF/DB panel consists of upper and lower face sheets, 2.286 mm (0.090 inch) starting thickness, which is then chem-milled to the design thickness requirement, and two 0.406 mm (0.016 thick) core sheets. The trailing edge, leading edge, tip, and closeout rib are fabricated to form an integral unit during the SPF/DB process (figure 3-23 (ref D707-702)). The panel is slotted at 52.698-percent chord from HSS 26.459 through 60.238 to provide attachments for the trunnion fitting (figure 3-24 (ref D707-703-003/004)). The fitting and strap (ref D707-704-003/004) are mechanically fastened to the panel with blind bolts. The stabilizer was designed to meet existing EI and GJ requirements.

3.2.2 COMPUTER-AIDED DESIGN (CAD) SYSTEM

The design and fabrication of SPF/DB structure is a complex operation which requires the accurate transmission of information between many departments. This information includes dimensions, the master dimension data package preliminary designs, detailed design drawings, tool designs, and manufacturing data. In addition, design changes which are frequently required in research and technology programs must be incorporated into the drawings in a timely mannner.

A CAD system was incorporated into the T-38 Horizontal Stabilizer Program to support design and fabrication of SPF/DB flight hardware. A flow diagram showing the CAD and fabrication process is presented in figure 3-25.

The T-38 horizontal stabilizer master dimensions were programmed into the CAD system. Basic planform dimensions and airfoil shape were stored in the computer so that section cuts could be taken in any direction to show mold line contours and true view shapes.

The data were accessed as required for the design layout through an Interactive Graphics terminal. Detail engineering drawings were dimensioned and plotted using the Calcomp Plotter and the design layout data base. Desired section cuts generated from the data base were scribed on aluminum templates using a Gerber plotter. The templates were then used to fabricate plaster masters and tracer patterns which were used to machine the SPF/DB die.

The diffusion bond stopoff pattern was also drawn at this time. The stopoff pattern for the T-38 horizontal is a complex variable sine wave pattern. The CAD system allowed the designer to draw one cycle of the intricate pattern and then successively mirror the image until the stopoff pattern for the entire core area is defined. Edge details of the stopoff pattern, which form the inflation manifold along the periphery of the tool cavity, was completed. The layering capability of the CAD system allows core-to-core and core-to-face-sheet patterns to be plotted independently to facilitate cutting of the patterns. A photograph of the Interactive Graphics terminal (Computer-Vision equipment) used to create the T-38 horizontal stopoff pattern is shown in figure 3-26.

Actual die cavity dimensions must be measured after the tool is machined. These dimensions are then compared with the stopoff pattern, and adjustments are made for thermal expansion characteristics and machining tolerances. Adjustments are made to the stopoff pattern by detailed trimming and plotting the pattern using X- and Y-axis scaling factors. The Gerber plotter is capable of independently scaling the X- and Y-axis so that the CAD stopoff drawing will define a core pattern which will accurately fit the machined die at elevated temperature.

The previous method of sizing the stopoff pattern was to manually draw the stopoff pattern (full scale) and then compare the pattern to the actual die cavity. Adjustments were then made for manufacturing tolerances and thermal expansion, and the stopoff pattern was modified. The drawing then incorporated on the automated drafting equipment, where a computer program was written to cut the stopoff pattern. This tedious process has been fully automated with the use of the CAD system, and no hand drawing of the stopoff pattern or separate computer programming is necessary.

After the stopoff pattern has been adjusted, a tape is made by the CAD system, which contains the core-to-core and core-to-face-sheet patterns as separate drawings. The tape is then used by the automated drafting equipment to have the stopoff patterns cut on an X-Y plotter (Gerber). (See figure 3-27.)

After the stopoff patterns are cut on the Gerber plotter, they are used in a phototemplate process to fabricate the silkscreens. The silkscreens control the pattern of stopoff material applied to the titanium sheets. The individual titanium sheets are then assembled to form the SPF/DB pack. This pack is then loaded into the hydraulic press and subjected to the SPF/DB heat and pressure cycle to form a T-38 horizontal stabilizer panel.

The application of the CAD system to a program productiing advanced technology flight hardware has many cost saving advantages. The following list shows the direct advantages of the CAD system as used on this program:

- o Master dimension data are directly available to the designer
- o Reduced drawing time
- o Rapid design changes
- o Automated drawing of complex stopoff pattern
- o Elimination of hand-drawn stopoff patterns
- o Simplified adjustment of stopoff pattern

3.2.3 STRUCTURAL ANALYSIS AND CORE TREND STUDY

The load distribution acting on the horizontal stabilizer was calculated, and the loads at the edges of the test specimen required to simulate the T-38 horizontal stabilizer were determined. Vertical shear loads and bending moments were located on the test panel in order to simulate the actual stabilizer at ultimate load.

The Rockwell International Finite-Element Model Computer program (RIFEM) was used to construct a model of the T-38 horizontal stabilizer. The T-38 model was divided into 440 modes and 380 elements of quadrilateral and triangular membranes. The double sine wave core of the horizontal stabilizer was transferred to a similar honeycomb quadrilateral shear and axial bar elements because the longitudinal and transverse shear moduli (GLC and GTC) are different throughout the horizontal stabilizer. The core was divided into 14 different webs and 14 support groups. The steel-spindle fitting was modeled as a quadrilateral bending beam running through the 52-percent chord plane. A graphic display of the NASTRAN finite-element model is shown in figures 3-28 and 3-29.

The loading condition (pressure distribution) received from Northrop Corporation was then applied to the T-38 model. The model was transferred to the NASTRAN program for analysis of stress, strain, displacement vector, and force acting on individual elements. A computer drawing of the horizontal stabilizer at ultimate load is in figure 3-30. Deflections have been magnified five times to graphically display the resultant shape.

The core properties used in the T-38 horizontal stabilizer model (figure 3-31) were calculated using predicted core properties. However, data from an ongoing IR&D test program subsequently revealed that these predicted values were too high; consequently, it was necessary to revise the NASTRAN model to reflect the new core properties.

The original core properties in the T-38 horizontal stabilizer model were replaced with the revised properties, and another finite-element analysis (FEA) was completed. Results of the FEA indicated that a zero margin of safety exists in some of the critical areas of the panel.

The core shear properties used in this analysis were based on a limited number of test specimens. Reliable data pertaining to the mean and standard deviation of the core properties cannot be obtained from such a small number of test specimens. Variances due to manufacturing defects tend to scatter the data. This could lower the core shear properties to unacceptable levels in critical areas. Therefore, the core shear properties must be improved before the core design is incorporated into the final design of the stabilizer.

As a result, a detail trade study of the sine wave core design was conducted. A baseline NASTRAN FEM of the core was prepared which modeled the configuration that had been fabricated and tested on the IR&D program. The baseline model was then modified by changing key variables in the design. The variables which were evaluated in the trade study were core sheet thickness, core sheet node width, and sine wave radius. A summary of the NASTRAN models which were run is given in table 3-IV.

Results of the sine wave core trade study are shown in figures 3-32 through 3-34. Figure 3-32 indicates that a variation in the core sheet thickness produces a linear improvement in the longitudinal core shear modulus, transverse core shear modulus, and compression modulus.

Figure 3-33 shows the effect of changing the core-to-core node band width. The bond width was changed from 0.127 (0.005 inch) to 5.080 mm (0.2 inch). The FEA models indicated that varying the core-to-core node bond width did not significantly change the core properties of the sine wave panels.

Figure 3-34 shows the results of the FEA model when the sine wave radius was varied. A very large increase in transverse shear modulus and compressive shear modulus was realized when the sine wave radius was changed from 35.56 (1.4 inches) to 25.40 mm (1.0 inch). The longitudinal shear modulus decreased with this change.

3.2.4 FABRICATION

During the course of this program, a parallel IR&D program which explored four-sheet technology produced data which could be applied to this program. The following paragraphs describe the accomplishments of this IR&D program so that the data can be extrapolated to the T-38 horizontal stabilizer design. Since both the panel fabrication and the subsequent structural test data are applicable, they are described in detail.

3.2.4.1 Material

All titanium material used for the performance of this technical effort was Ti-6Al-4V alloy purchased to MIL-T-9046 specification, type III, composition C, requirements. A total of 13 different heats of titanium sheet material in varying thicknesses were used during the program. Testing on the heats was conducted to establish flow-stress properties as a function of strain-rate and strain-rate sensitivity index (m) at 898.89° C (1,650° F), used as a basis for controlling the SPF process. Only those heats of material used in sandwich core applications were normally tested; however, when test data from previous sampling were available, they were also used for the less critical face sheet applications. The test data from elevated-temperature tensile testing were analyzed to determine the proper pressure-temperature cycle.

3.2.4.2 Fabrication Considerations

Fabrication of the SPF/DB four-sheet sandwich horizontal stabilizer structure presented many new challenges, including the following:

1. Large four-sheet sandwich panels
2. Thick four-sheet sandwich panels
3. No prior forming analysis
4. Thin core design
5. Panel edge forming
6. Internal pressure to SPF multiple sheet panels
7. Design constraints (sine wave core thickness and shape)
8. Face-to-core-sheet thickness ratio
9. Dot diameter as a function of dot core panel depth
10. Narrow core-to-core bond widths for double-truss core panel

The largest four-sheet SPF/DB sandwich previously fabricate was a 228.6 by 228.6 mm (9 by 9 inches) panel with a maximum depth (panel thickness) of 25.4 mm (1.0 inch). It was assumed that, in three-sheet technology, the fundamental mechanisms in SPF/DB processing are essentially insensitive to size. However, large four-sheet technology panels with increased depth and thin core sheets represented an unknown area of SPF/DB technology.

Forming analyses had been established, at least through the initial stage of forming, for three-sheet sandwich technology. Similar forming analyses have not been made for multiple-core forming.

Another area of concern was the panel edge and involved the degree of core rotation occurring during SPF, a condition understood and accounted for in the design of a three-sheet SPF/DB sandwich. However, with forming occurring in both directions from the center, the rotation effect was an unknown factor.

In three-sheet sandwich SPF/DB processing, after bonding, internal pressure breakthrough occurs on both sides of the core sheet simultaneously and is determined by measuring the exit gas flow. With multiple-core sheets, breakthrough must occur in three separate areas (between the upper face and upper core sheets, between the two core sheets, and between the lower face and lower core sheets). Breakthrough in four-sheet panels is determined by one exit gas measurement. Proper pressure breakthrough of all three areas cannot be absolutely determined with only one indicator because a positive reading will result even if only one passage opened.

Design constraints also imposed processing factors not previously fully established. In sandwich panels, core geometry plays an important role in successful processing and face-to-core sheet thickness ratio, and narrow center bond width of the double sine waave core and the ratio of dot diameter to panel thickness in the dot core configuration were factors in the SPF process which had not been fully established.

3.2.4.3 Process Parameter Selection

The process parameters used to successfully form the four-sheet sandwich were based on previous experience in forming small sandwich panels and in forming three-sheet SPF/DB structure. Therefore, the initial forming trial on 711.2 by 711.2 mm (28 by 28 inches) test development panels was to use 2.068 by 10^6 Pa (300 psi) for 2 hours for the DB cycle. This pressure was then removed, and a predetermined schedule of increasing forming pressure between the sheets was used to reach again 2.068 by 10^6 Pa (300 psi). The pressure temperature cycle was based on three-sheet technology procedure. The assumption made was that one-half of the forming core is analogous to a three-sheet sandwich forming condition.

3.2.4.4 Tooling

Tooling for the subscale sandwich panels was fabricated from 22Cr-4Ni-9Mn steel. The tooling consisted of two containers, an upper and a lower, which were in existence from previous work. To obtain the desired configuration of the double-core sandwich, each tool cavity was fitted with a steel insert as shown in figure 3-35.

The upper insert was mechanically pinned and welded to the upper tool. The existing containers incorporated cavity peripheral ramps of 60 degrees on the upper tool and 45 degrees on the lower. Vent holes were placed in the radius area of the individual cavities to vent the argon gas during the forming (expansion) cycle. Tooling surfaces in contact with the titanium were sprayed with a boron nitride parting compound.

The preliminary design of the horizontal stabilizer superplastic form die is shown in figure 3-36 (ref SK17091). It was anticipated that changes and design refinements to reduce manufacturing risk would result from development tests.

3.2.4.5 Titanium Sheet Preparation

Titanium sheet preparation consisted of shearing to a size commensurate with the tool size (approximately 635 by 635 mm (25 by 25 inches)). Grooves were placed in the face sheets to match the core sheet slots for placement of the argon gas tubes. Each core sheet was drilled with a specific hole pattern to allow gas movement throughout the truss area during forming (this is not required when fabricating the dot core configuration since gas movement in this design is not restricted).

All sheets were cleaned in accordance with Rockwell specification requirements for DB surfaces.

Yttria stopoff was applied selectively to surfaces of the two core sheets to allow selective bonding of those areas that would ultimately form the truss core. Application of the stopoff was controlled by silk screens. The coarse yttris (yttrium oxide) which is 99.5-percent Y2O3, is formulated into paint-like mixtures using an acrylic carrier and acetate solvents.

The stopoff pattern to be applied to the core sheets is generated from the final engineering design. The CAD system was used to produce a stopoff pattern by digitizing to accommodate an automatic drafting machine which produced and cut the final pattern. This pattern was used to make a silk screen. Existing frame was used for the silk screen stopoff application.

An actual sine wave pattern used to fabricate a producibility test panel is shown in figure 3-37.

3.2.4.6 Component Fabrication

The pack assembly for each part consisted of two each face and core sheets, the argon gas inlet and outlet tubes, and, in some cases, two internal doublers. The gas tubes were stainless steel of either 1.78 mm (0.070 in) or 2.29 mm (0.090 in) diameter. Slots and grooves to accommodate the steel gas tubes, were cut into the core and face sheets to the stopoff pattern area. Each tube protruded 3.18 mm (0.125 inch) into the stopoff patterns area. The titanium sheets, properly aligned and positioned in relation to each other, were tack-welded together and placed on the tooling as shown in figure 3-38. The containers with their inserts and the pack were positioned between heating and inserted into a 300,000 kg (300-ton) hydraulic press as shown in figure 3-39.

The four-sheet sandwich panels were fabricated by gas diffusion bonding the flat sheets together in selected areas as determlned by the stopoff pattern and then superplasticially expanding them to fill the tool cavity. Diffusion bonding time and pressure were determined initially by an analytical prediction curve which had been previously established. Variations were made to the diffusion bonding cycle during the panel fabrication. Standard practices were applied to obtain pressure breakthrough after bonding and prior to forming. However, these procedures were also varied in order to achieve best result.

The basic steps in SPF/DB processing of the panels were as follows:

1. Heat to 899° ($\pm 10^{\circ}$)C (1,650° ($\pm 50^{\circ}$)F)

2. Diffusion bond with argon gas pressure (typically 207 N/cm^2 (300 psi) for 2 hours)

3. Pressure breakthrough (as pressure with or without a vacuum assist)

4. Superplastic forming in accordance with a predetermined pressure-time cycle based on an established analysis (there was no analysis for the four-sheet technology)

5. Cool and remove

A total of 12 four-sheet SPF/DB sandwiches were fabricated. A photograph of a typical panel is shown in figure 3-40. All panels were 711 by 711 by 60 mm (28 by 28 by 2.35 inches), with the exception of the last one which was a 229 by 229 mm (9- by 9-inch) panel. Truss core configurations include sine wave, modified sine wave, and dot core. Other variations included bond node width, the use of doublers, strain rates, and processing changes. Table 3-V is a summary of all parts fabricated. The details are discussed in the following paragraphs.

3.2.4.7 Initial Panels (Parts 1, 2, 3, and A-1)

The initial group of 711 by 711 mm (28- by 28-inch) sandwich panels was fabricated in two separate stages: (1) diffusion bonding against a flat panel, and (2) superplastic forming in a double-tool cavity. The core configurations were sine wave and dot core. All tools used were sprayed with boron nitride, and yttria was used on all stopoff patterns applied by the silk screen method. Two each 1.78 mm diameter (0.070-inch-diameter) inlet and outlet tubes for argon gas were placed in between the grooved face sheets and the slotted core sheets. Stage 1, gas bonding, was accomplished using a flat-base tool and a cavity upper tool, both made from 22Cr-4Ni-9Mn steel. In each case, the face sheets were extended to the edge of the tool while the core sheets were sized to fit the interior cavity as shown in figure 3-41.

Stage 2, superplastic forming, was done in the double-cavity tools where the bonded pack was suspended between the cavities of the upper and lower dies during heatup while a controlled differential pressure was held on each side of the titanium pack to prevent sagging caused by gravity. The gas pressure system was set up to maintain a slightly higher pressure in the bottom cavity to support the pack at elevated temperatures. When forming temperature was reached, gas pressure was introduced between the titanium sheets to obtain breakthrough prior to application of the pressure-time (P-T) cycle. Breakthrough for each of the panels varied, but ranged from 1.38 to 10.34 N/cm^2 (2 to 15 psi) in a few minutes. Panel 2 experienced an inconsistent breakthrough, while panel A-1 indicated a partial breakthrough at 2.76 N/cm^2 (4 psi) and complete breakthrough at 6.90 N/cm^2 (10 psi) with assistance from vacuum in the tool cavity areas.

The P-T cycle was applied immediately after breakthrough. The P-T cycles were generated based on the following criteria:

1. It was assumed that one-half of the double-core sandwich modeled a three-sheet sandwich condition, and an existing sine wave truss core computer program could be used.

2. Strain rate was selected on the basis of previous experience with three-sheet sandwich panels and on computer program studies which provide ratios of face-sheet-to-core-sheet thicknesses to indicate whether there are likely to be grooving problems.

3. A cross section was taken through a dot core configuration, and the resulting geometrical section was used in a truss core computer program to arrive at a P-T cycle.

A typical P-T cycle is shown in figure 3-42. Each of the parts fabricated used a specific P-T cycle tailored to its configuration and material properties. The peak pressure and rate of pressure change up to the dwell time varied with panel geometry (sine wave or dot core) and with material flow stress and the strain rate applied. Dwell time and rate of pressurization increase to the 207 N/cm^2 (300 psi) hold level are typical.

Fabrication of the initial group of four panels resulted in a ruptured core in all cases as shown through radiographic examination and confirmed by visual examination after cutting. As table 3-V shows, the strain rate applied was decreased on the sine wave panels and on the dot core panels since the initial fabrication resulted in ruptured panels. However, strain rate apparently was not the problem. Further investigation revealed that uncontrolled core expansion occurred due to the use of to the edge of the pack and the core sheets which did not extend to the edge of the pack and the resulting initial large stopoff manifold area. This allowed breakthrough to occur around the edge of the core sheets. On the basis of these runs, the following actions were taken:

1. Core sheet size was extended to the edge of the pack identical to the face sheet sizes.

2. Runs were made showing that a single heat cycle was feasible because differential pressure above and below the sheets could be controlled.

3. Due to weight considerations, face and core sheet thicknesses were reduced to 1.27 mm (0.050 inch) and 0.43 mm (0.017 inch), respectively.

4. The face-to-core-sheet thickness ratio of 3:1 was maintained.

5. A double-dot core sandwich panel was prepared.

6. The double sine wave configuration was considered for redesign.

Based on the procedures established in the fabrication of the previous panels, which established the feasibillty of paney manufacture with one thermal cycle, part 4 was fabricated using this process. The old and new methods are shown in figure 3-43. The procedure for the fabrication was to directly measure the gas pressure differential between the upper and lower die cavities and to provide a slight positive gas pressure in the lower die cavity to support the titanium pack during heatup to 899° C (1,650° F). Gas-diffusion bonding was then accomplished prior to pack breakthrough and expansion. This one-step heat cycle was considered a significant advancement in SPF/DB technology.

Part 4 was a double-dot core configuration with 1.27 mm (0.050-inch) face sheets and 0.43 mm (0.017-inch) core sheets, as shown in table 3-V. The titanium sheets and tooling were prepared as previously discussed. Although the established procedures were followed without incident, the core ruptured. Postforming analysis of this panel and other dot core panels previously fabricated revealed that a satisfactory dot core panel had not been produced with a height-to-dot-diameter ratio greater than 1:1, while this panel had a ratio of about 3:1. Since manufacturing feasibility was not demonstrated with this design, the dot core was eliminated from consideration and emphasis was placed on the sine wave core configuration.

Panels A-2 through A-5 were all four-sheet sine wave truss design, and all were processed in a single heat cycle. Parts A-2, A-3, and A-5 used 1.27 mm (0.050-inch) face sheets and 0.43 mm (0.017-inch) core sheets, while part A-4 used 1.27 mm (0.050-inch) doublers in conjunction with 1.27 mm (0.050-inch) face sheets and 0.43 mm (0.017-inch) core sheets (table 3-V). All panels used characterized material data in deriving the P-T cycles with variations in planned strain rates. A controlled breakthrough was obtained through the application of a vacuum on both sides of the face sheets during processing.

Part A-2 was unique in that it represented the first panel designed by computer-aided design (CAD) with intermediate steps using computer-aided manufacturing (CAM). Engineering drawings of the panel and the core sheet stopoff pattern were generated by CAD, while the stopoff pattern was produced through CAM.

The sine wave truss core pattern incorporated a varying width bond node which resulted in a constant truss core angle for the length of the panel.

Part A-2 was formed without rupturing the core. This represented the first successful double sine wave core produced to the specified depth. However, the face sheets were deeply grooved, following the sine wave pattern. This surface condition was attributed to partially pinched argon gas tubes which influenced the application of the planned P-T cycle.

Part A-3 was processed identical to the previous part with the exception of a tool relief in the area of the gas tubes to prevent tube pinching and a decrease in the planned strain rate. After processing, X-ray inspection indicated some core ruptures along the outer edges of the panel along the first and second core webs. This failure was attributed to the rotational effects of the face sheets expanding into the tool cavity during forming. The stretching of the skin into the corners shifted the node locations, causing excessive core sheet stretching and subsequent rupture. However, the panel was usable for some tests.

Panel A-4 was processed with the same face and core sheet thickness as was part A-3, but doublers were added to the sandwich interior in the tool cavity area to minimize the core rotation. Each doubler was edge chamfered approximately 45 degrees, sized to fit the bottom tool cavity area, and placed between the face and core sheets. The doublers were 1.27 mm (0.050 inch), which increased the actual face sheet thicknesses to 2.54 mm (0.100 inch). Standard procedures of SPF/DB fabrication were used, and the panel was successfully formed.

Part A-5 was processed identically to part A-4 to provide additional test material. Although some ruptured areas were indicated by X-ray inspection, the panel was usable.

In part TP-1, the truss core sine wave configuration was changed to provide a 25.4 mm (1.0-inch) sine wave radius rather than 35.56 mm (1.4 inch), to increase panel strength. The core node bond width was also changed to 2.54 mm (0.100 inch), and a new pattern and a silk screen were provided. The 1.27 mm (0.050-inch) face sheets and doublers and the 0.43 mm (0.017-inch) core sheets thicknesses remained. The SPF/DB procedures used in fabricating the previous panels were used, with the exception that the planned strain rate was reduced from previous fabrication runs. Postexpansion inspection of the panel indicated that the core was ruptured in numerous locations, with the majority of ruptures located a tone end of the panel. The rupturing of this panel core indicated that attempting to form a full-scale horizontal stabilizer with 0.41 mm (0.016-inch) thick core would pose unacceptably high risks.

The panels which were successful (A-2 through A-5) were sectioned and prepared for testing. Core shear specimens, bending beams, and core specimens were prepared from the panels.

The core shear specimens were fabricated by cutting sections from the test development panels. Specimens were sawed into rectangular sections, and then steel plates were bonded to the face sheets in order to test for core shear allowables. The completed test specimen and the test setup are shown in figure 3-44. Closeup photographs of longitudinal and transverse specimen are shown in figures 3-45 and 3-46.

3.2.5 CORE TRANSITION DEVELOPMENT

One of the most significant accomplishments of the development program was the four-sheet to three-sheet transition of the producibility test specimens which was undertaken following the results of the four-sheet test specimens. The low allowables achieved during this phase necessitate an alternative design concept which consists of a four-sheet design in the deep section, transitioning to a three-sheet design around the periphery of the tail. This design contrasted with the original four-sheet design over 100 percent of the stabilizer. The four/three-sheet design produced the same weight as the lighter gage four-sheet-only design but required a transition demonstration. The tapering geometry of the T-38 horizontal stabilizer is generic for many structures. Therefore, it was necessary to develop a method of dropping one of the panel core sheets when the stabilizer tapered down to less than 38.10 mm (1.5 inches).

Two design concepts were considered. First, the double-straight truss core at one end changing to a single, straight truss core on the other end, as depicted in figure 3-47. Second, the double sine wave truss core changing to single sine wave truss core, as shown in figure 3-48 and 3-49.

The second concept was selected based on the preferred T-38 design, and a 228.6 (9 inches) by 228.6 (9 inches) by 41.15 mm (1.62 inches) deep producibility panel was fabricated. The panel was made of 1.78 mm (0.70 inch) thick outer face 6Al-4V titanium sheets and 635 mm (0.025 inch) thick 6Al-4V titanium core sheets with a cutout on one of the core sheets as shown in figure 3-48. The lower half of the panel has 30-degree draft, 19.05 mm (0.75 inch) deep peripheral closeout, while the upper half has a 45-degree, 17.27 mm (0.68 inch) deep peripheral closeout. A photograph of this core transition specimen is shown in figure 3-49. The center node (core-to-core bond) gradually moves from the center of the panel to one of the face sheets. This core transition specimen is the first of its kind ever built and is considered a significant breakthrough in SPF/DB technology.

3.2.6 JOINT TEST DEVELOPMENT SPECIMEN

The T-38 spindle/horizontal stabilizer splice joint was considered the most critical design area of the stabilizer. The transfer of loads from the spindle fitting to the steel straps, combined with a change in the panel cross section, complicated the analysis of the specimen. The end of the slot which was to be cut in the panel to accommodate the center web of the spindle results in a stress concentration in this splice area.

A joint test development specimen was designed to test this critical stabilizer area prior to full-scale fabrication. A 635 by 635 mm (25 by 26 inch) SPF/DB sandwich panel with steel splice straps and simulated spindle fitting was designed during task 2. The detail drawing is shown in figure 3-50.

The panel was a constant 45.7 mm (1.8 inch) deep except for the joggle area which fits under the spindle and straps. Loading blocks are provided along the outer edges of the panel to introduce vertical shear and moments to match actual loads of the full-scale stabilizer in the critical area. The inboard end of the spindle was designed to be fixed to the loading structure as a cantilever beam. Figure 3-51 shows a drawing of the joint development test specimen prior to testing.

It was planned that test loading would be applied in 20-percent increments up to 60 percent of design ultimate and 10-percent increments thereafter until failure. Strain gages were to be placed on the sandwich panel and spindle to collect data as the test proceeded. These data were to be correlated to test predictions and used to modify analysis methods, as required.

Tooling for the specimen was completed; however, the program was terminated before fabrication and testing of the specimen was underway.

3.2.6.1 Joint Test Specimen Tooling

Standard tooling procedure for fabricating tapering panel SPF tool dies is to make full-scale metal templates, defining the mold line at various stations, and then use these templates to fabricate a plaster master. An epoxy-faced tracer pattern is then taken from the master model for machining. However, since the test part for this program requires only a constant-thickness part, a full-scale wooden tracer pattern was built to eliminate the plaster tooling. A photograph of the completed wooden master is shown in figure 3-52.

Using the wooden master and tracer machining techniques, the upper and lower tool dies were prepared as shown in figure 3-53. The tool alignment keys can be seen on the lower die, and the corresponding slots on the upper die. The steel cantelever I beam, straps, and loading channels were rought machined as shown in figure 3-54.

All tests performed during this program were completed as planned. The test results for all completed specimens are shown in table 3-VI. The tests yielded very low mechanical properties which were attributed to a combination of center node rotation and curvature of the thin expanded core.

3.2.7 DEVELOPMENT TESTS

The four-sheet deep-core sandwich panel was a new design concept for which mechanical properties were limited. During the preliminary design phase, existing three-sheet technology data and analysis methods were used to extrapolate allowables for the stabilizer. Test development and detail design proceeded simultaneously with the assumption that testing would verify predictions.

The specimens were prepared, and testing was conducted to determine the actual core and face sheet mechanical properties of the four-sheet sandwich. All specimens were sine wave sandwich configuration and 59.7 mm (2.35 inches) deep (which was representative of the stabilizer panel in the area of the rootrib/spindle intersection).

The first two bending beams were potted with Rigidex, a low-temperature melting compound, to fill both ends of the beams so that the loading bars would not crush the core during testing. The Rigidex was scheduled to be removed after testing so that flatwise compression tests could be run on the undamaged portions of the specimens.

During testing, the Rigidex material cracked prior to beam failure, reducing confidence in the test results. The remaining four untested beam specimens were reworked, and the Rigidex was replaced with an epoxy potting compound prior to testing.

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4.0 EVALUATION OF RESULTS

This program, in conjunction with Rockwell's concurrent IR&D program, has laid the foundation for the fabrication of full-scale SPF/DB titanium structure employing double-truss core sandwich. This has been made possible by trade studies which optimized the design configuration, by the generation of an expanded test data bank, by a detail study of the proposed core configuration, by the development of improved fabrication processes, and by the application of computer-aided design and manufacturing.

4.1 DESIGN OPTIMIZATION

The two most critical design features were optimized during task 1 trade studies. The first was the core configuration study which established the double-truss sine wave core as the optimum compromise between weight and manufacturing risk. The second study investigated a wide range of methods for attaching the spindle to the surface. This resulted in the selection of a spindle which is machined to an I-beam configuration with blind fasteners attaching the flanges to the mold line surfaces of the stablizer.

4.2 TEST DATA

The predicted allowables used for the initial design of the stabilizer were based on an extrapolation of single-truss core data since double-truss core data did not exist at the time. Although the extrapolation techniques have proved to be relatively accurate for single-truss core sandwich analysis, test data proved this approach to be excessively unconservative when applied to double-truss sandwich. These test data (shown in table 3-VI) provide accurate values for core compression ultimate, core compression modulus, face sheet compression ultimate, core shear ultimate, and core shear modulus for several data points.

4.3 CORE TREND STUDY

A detail finite-element analysis of double-truss sine wave core was conducted using the NASTRAN computer program. The purpose of the study was to develop trends which, when combined with producibility considerations, would produce the lowest weight core consistent with low-risk fabrication. Although this task was part of Rockwell's ongoing IR&D program, the results are included because of their pertinence to this program.

The variables which were evaluated in the trade study were core sheet thickness, core sheet node width, and sine wave radius.

Results indicate that improving the core sheet thickness improves the longitudinal core shear modulus, transverse shear modulus, and compression modulus. The node bond width was changed from 0.13 (0.005 inch) to 5.08 mm (0.20 inch), and results indicated a minimal improvement on the core properties. A large increase in transverse shear modulus and compressive shear modulus was realized when the sine wave radius was changed from 35.56 (1.4 inches) to 25.4 mm (1.0 inch) with a slight decrease in the longitudinal shear modulus.

4.4 FABRICATION

4.4.1 FOUR-SHEET PANEL

The SPF/DB four-sheet sandwich design for the horizontal stabilizer structure presented many new fabrication challenges, such as forming parameters, thin core behavior in the SPF/DB cycle, edge rotational behavior of the core, and the effects of the sine wave core on forming. It is also the largest and deepest SPF/DB four-sheet sandwich panel ever attempted using the SPF/DB process.

Producibility panels were fabricated based initially on the forming data available from the three-sheet technology. An interactive design/fabrication process was conducted, resulting in optimum producible four-sheet sandwich configurations. The parameters defined included face-to-core-sheet thickness ratio, dot-diameter-to-panel-depth ratio (for dot core sandwich), the core-to-core bond width, and the core-to-face-sheet bond width. These are shown on the drawing in figure 3-7 through 3-9.

4.4.2 SINGLE HEAT CYCLE

One of the fabrication techniques developed during Rockwell's IR&D program on four-sheet sandwich will offer particular benefits to a full-scale double-contour structure such as the T-38 horizontal. This is the single-cycle SPF/DB process in which the diffusion bonding process and the forming process are accomplished in the same cycle. Although this is the normal procedure for sandwich structure in which both faces are parallel for a structure with an airfoil shape, a two-step process is normally used. First, the titanium pack would be bonded together against a flat die. Then, the pack would be cooled down, placed in a second die with the proper upper and lower surface contours, reheated, and expanded.

In the improved process, the pack is diffusion bonded in a die with the desired contour by applying pressure to both sides of the pack, which allows it to remain flat during this part of the process. After bonding, the pack is expanded into the die to produce the fully formed part. This results in a substantial reduction in fabrication time, as well as reduction in the tooling required.

4.4.3 THREE-SHEET-TO-FOUR-SHEET TRANSITION

One of the primary advantages of double-truss core is the low node spacing obtainable with deep sections, thus providing high buckling allowables for the face sheets. However, in thin sections, such as the leading or trailing edge and the tip of the stabilizer, single core can provide adequate node spacing with a 50-percent reduction in core weight (compared to double truss core of the same thickness). The ideal configuration, therefore, is double-truss core transiting into single-truss core in the thinner sections of a panel. A concept was developed, and a 229 by 229 mm (9 by 9 inches) producibility panel (figure 4-1) was successfully fabricated.

The panel uses four-sheet construction on one end and changes to standard three-sheet construction on the opposite end. The center node (core-to core bond) gradually moves from the center of the panel to the inner side of one of the face sheets. This core transition is the first of its kind and is considered a significant breakthrough in SPF/DB technology.

4.4.4 APPLICATION OF COMPUTER-AIDED DESIGN AND MANUFACTURING (CAD/CAM)

This Rockwell CAD/CAM system is a complete automated system that integrates product development from the first design idea to the finished product. The CAD/CAM system was incorporated into the T-38 horizontal stabilizer to reduce the cost of design and fabrication cycle.

The T-38 horizontal stabilizer master dimensions were programmed into the system. The designer accessed the data required for the design layout on a CRT and then developed the design in detail. The detail drawing was plotted using the Calcomp plotter.

The core stopoff definition was also drawn as shown in figure 4-2 and plotted directly on the pattern using the Gerber plotter with a needle-like stylus. Section cuts generated from the data base were scribed directly on the aluminum template and used to fabricate plaster master and tracer pattern.

The manufacturing engineer also can call up the stabilizer designs on the graphic display and generate machine tool paths graphically for controlling the tool fabrication in lieu of a plaster master and tracer pattern. The system computes and displays all tool path coordinates and assures that what is displayed on the screen will be reproduced in the shop. This results in dramatically lowered costs.

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5.0 RECOMMENDATIONS

The technical progress during this program has indicated that SPF/DB titanium structure can be applied to supersonic aircraft primary structure. Although feasibility of some of the concepts has been demonstrated in this program, more development will be required in order to minimize the uncertainty and derive a more accurate prediction of the properties. The following are additional specific recommendations:

- Additional development of four-sheet technology
- Development of post diffusion bonding (i.e., fittings, straps, etc)
- Consideration of other materials that demonstrate superplastic properties
- Repairability of SPF/DB structure

Table 3-I

CORE COMPARISON*

	Thickness, $\bar{t}$ mm (in.)	Weight g/cm^2 (lb/in^2)
Straight truss core		
Single truss	4.95 (0.195)	2.18 (0.031)
Souble truss	4.11 (0.162)	1.83 (0.026)
Sine wave truss core		
Single truss	3.84 (0.151)	1.69 (0.024)
Double truss	3.30 (0.130)	1.48 (0.021)
Dimple core		
Single	3.78 (0.149)	1.69 (0.024)
Double	<3.39 (0.130)	~1.41 (0.020)
Aluminum baseline		2.04 (0.029)

*Near root at Midchord

Table 3-II

PRELIMINARY DESIGN CONCEPT SUMMARY

Concept		Advantages	Disadvantages
A	Existing fitting inserted into SPF/DB panel and fastened with blind bolts. Spanwise double truss core.	• Existing fitting can be used with minor modifications. • Simple core design running near % planes.	• Will not meet design requirements. • Difficult to fit spindle to inside surface of stabilizer. • Poor load path design.
B	New fitting with continuous root rib design. Shear tie to root rib through DB filler blocks.	• Easy to shim fitting because of shallow penetration. • Leading and trailing edge closeout concepts are promising.	• Will not meet design requirements. • High stress concentration at fitting/stabilizer intersection. • Center fasteners pick up much of the load.
I.	Existing forging is fit over solid titanium block.	• Simple fitting. • Good clamp up.	• Does not meet design requirements. • Heavy design. • Insufficient fastener spacing.
II.	Smaller fasteners used for proper spacing. Two blind fasteners added. Solid titanium block design.	• Simple fitting • Good clamp up.	• Does not meet design requirements even with added fasteners and spacing.
III.	Solid forging with three large fasteners.	• Simple fitting. • Good clamp up.	• Large moldline bump required. • Heavy. • Requires very thick skins.
IV.	Double shear fitting design using existing forging.	• Increased M.S. on bolts. • Smaller diameter bolts possible.	• Complex machining and fitup required.
V.	Extension welded on to existing forging. Root rib loads carried through fitting.	• Symmetrical bolt pattern about spindle centerline. • Good clamp up.	• Weld and subsequent heat treat required. • Moldline bump required.
VI.	New forging or weldment machined to fit over stabilizer.	• Continuous root rib. • Simple fitup.	• Large moldline bump required. • Poor clamp up may lead to fatigue problem.
VII.	Solid spindle fitting with continuous root rib.	• One piece root rib. • Good clamp up.	• Fitup more difficult. • Moldline of root rib requires additional tooling.
VIII.	"I" beam spindle fitting.	• Fits within moldline constraints. • Good load path design. • Gradual load pickup.	• Stress concentration at end of fitting. • Slot must be cut in stabilizer panel.

Table 3-III

DEVELOPMENT TEST PLAN

Test Type	Loading	Core Direction	Size	Quantity
Core Properties	Flatwise Compression	—	20.3 x 15.2 cm (8 x 6 in)	2
	Plate Shear	Longitudinal	25.4 x 12.7 cm (10 x 5 in)	3
		Transverse	40.6 x 16.5 cm (16 x 6.5 in)	3
Face Properties	Bending Beam	Longitudinal	55.9 x 16.5 cm (22 x 6.5 in)	2
		Transverse	55.9 x 16.5 cm (22 x 6.5 in)	2
Joint Development	Complex V, M, T	Transverse	71.1 x 71.1 cm (28 x 28 in)	1

Table 3-IV

FOUR-SHEET SANDWICH NASTRAN MODELS

Core Sheet Variation (mm (in.))			Constants (mm (in.))
A 0.41 (0.016)	B1 0.64 (0.025)	B2 0.81 (0.032)	Sine Wave Radius = 25.4 (1.0)

Node Width Variation (mm (in.))			Constants (mm (in.))
A 5.08 (0.20)	B 1.90 (0.075)	C 0.13 (0.005)	Sine Wave Radius = 25.4 (1.0) Core Sheet = 0.41 (0.016)

Sine Wave Radius Variation			Constants
A 25.4 (1.0)	D 35.56 (1.4)		Core Node Width = 5.08 (0.20) Core Sheet = 0.41 (0.016)

Table 3-V.

FABRICATION SUMMARY

Part Ident.	Sheet Thick. Face	Sheet Thick. Core	Bond/ Form	Configuration	Vacuum	Strain-Rate	Material Charact.	Results
1	.088	.033	Bond form	Sine wave	- No	- 1.2×10^{-3}	- No	Ruptured
2	.085	.032	Bond Form	Dot	- No	8×10^{-3}	No	Ruptured
3	.085	.032	Bond Form	Dot	- No	$.8\times10^{-4}$	Yes	Ruptured
4	.050	.016	Both	Dot	Yes	$.8\times10^{-3}$	Yes	Ruptured
A-1	.087	.033	Bond Form	Sine wave	- No	- 9×10^{-4}	- No	Ruptured
A-2	.050	.017	Both	Sine wave	Yes	$.9\times10^{-3}$	Yes	Good
A-3	.050	.017	Both	Sine wave	Yes	$.2\times10^{-3}$	Yes	Usable
A-4	.100	.017	Both	Sine wave	Yes	$.5\times10^{-3}$	Yes	Good
A-5	.0475	.017	Both	Sine wave	Yes	$.4\times10^{-3}$	Yes	Usable
TP-1	.130	.017	Both	Sine wave	Yes	$.2\times10^{-3}$	Yes	Ruptured
T-38/9	.017	.025	Both	Core transition	No	$.1\times10^{-3}$	Yes	Good

Table 3-VI

TEST SPECIMEN RESULTS
(Stresses in N/cm^2 (psi))

Test Type	Direction	Specimen	Core Compression		Face Ult Stress	Core Shear	
			ult	E'c		ult	G'c L, T
Flat-Wise Comp.		A4-2-1	44.62 (64.71)	3,956 (5,738)			
		A4-2-2	40.82 59.20	2,994 (4,343)			
Bending Beam	Long.	A5-1			30,051 (43,585)		
		A5-2			36,605 (53,091)		
		A5-3			37,100 (53,809)		
	Transv.	A4-1			22,793 (33,058)		
		A4-2			21,947 (31,832)		
		A4-3			21,610 (31,342)		
Plate Shear	Long.	A3-1				61.2 (88.8)	5,221 (7,573)
		A3-2				59.6 (86.4)	7,173 (10,404)
	Transv.	A3-3				56.7 (82.3)	1,000 (1,450)*
		A3-4				54.7 (79.3)	724 (1,050)*
		A3-5				30.8 (73.7)	648 (940)*

*At = 41 N/cm^2 (60 psi)

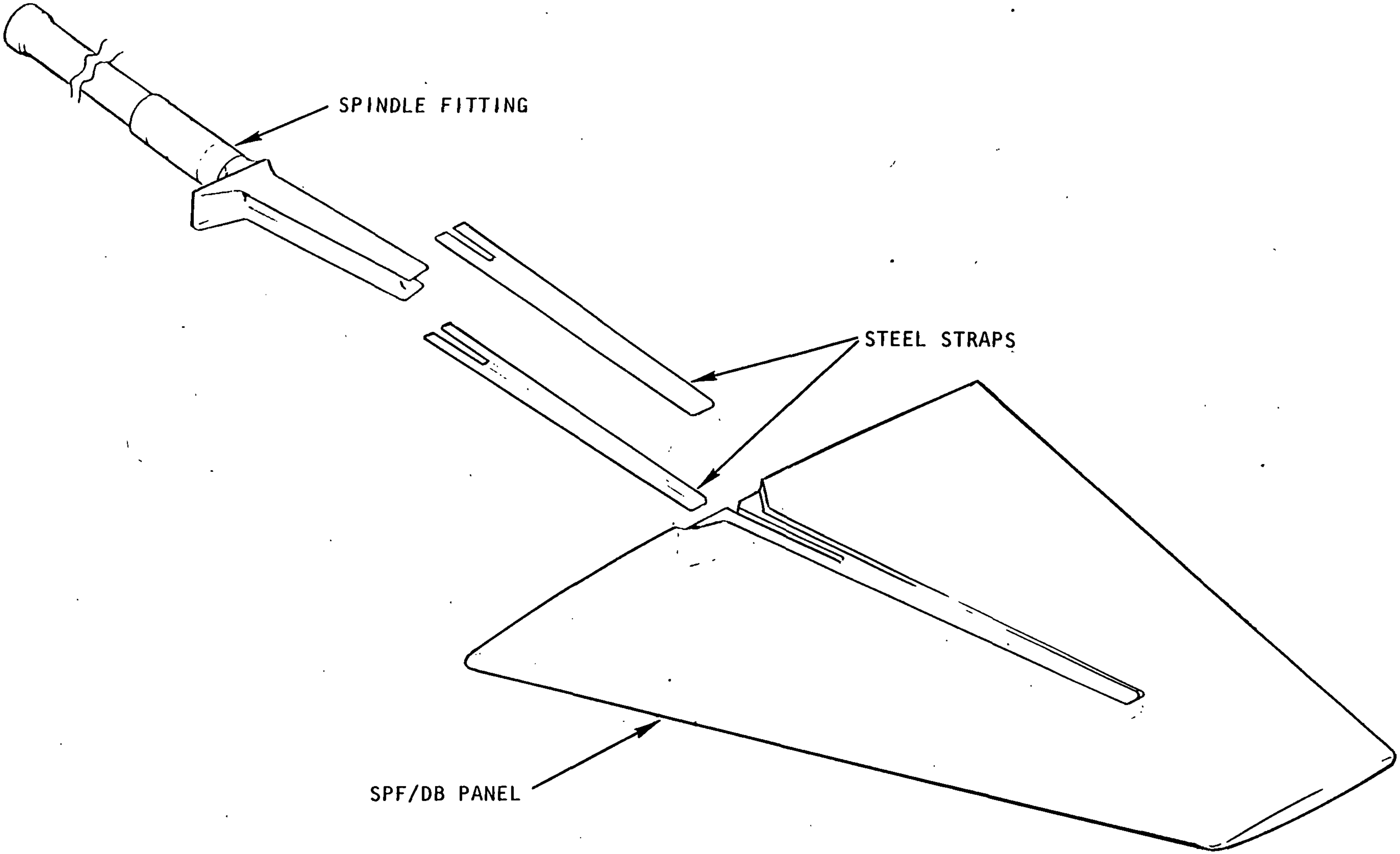


Figure 1-1. SPF/DB Stabilizer Assembly

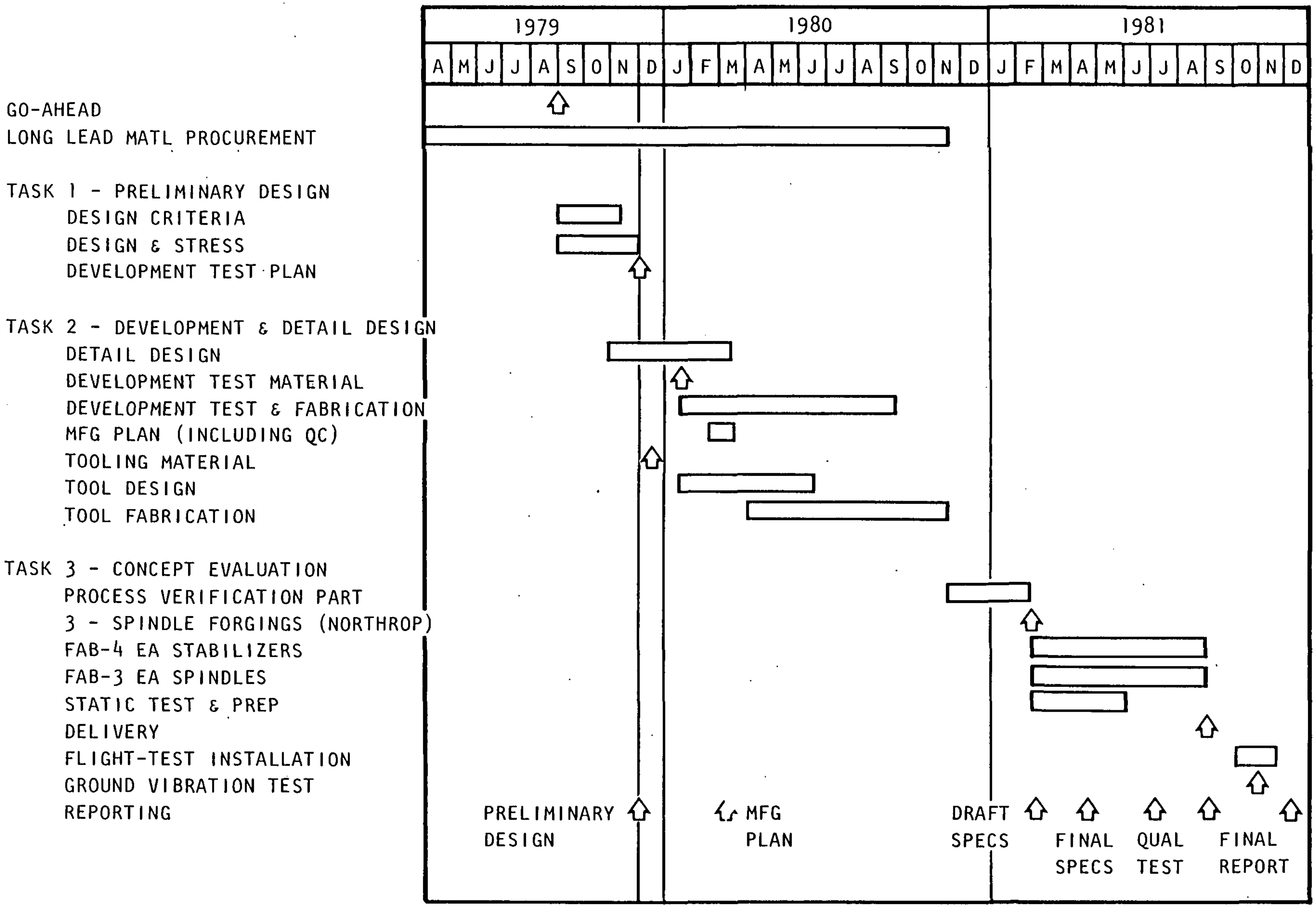


Figure 2-1. Program Schedule

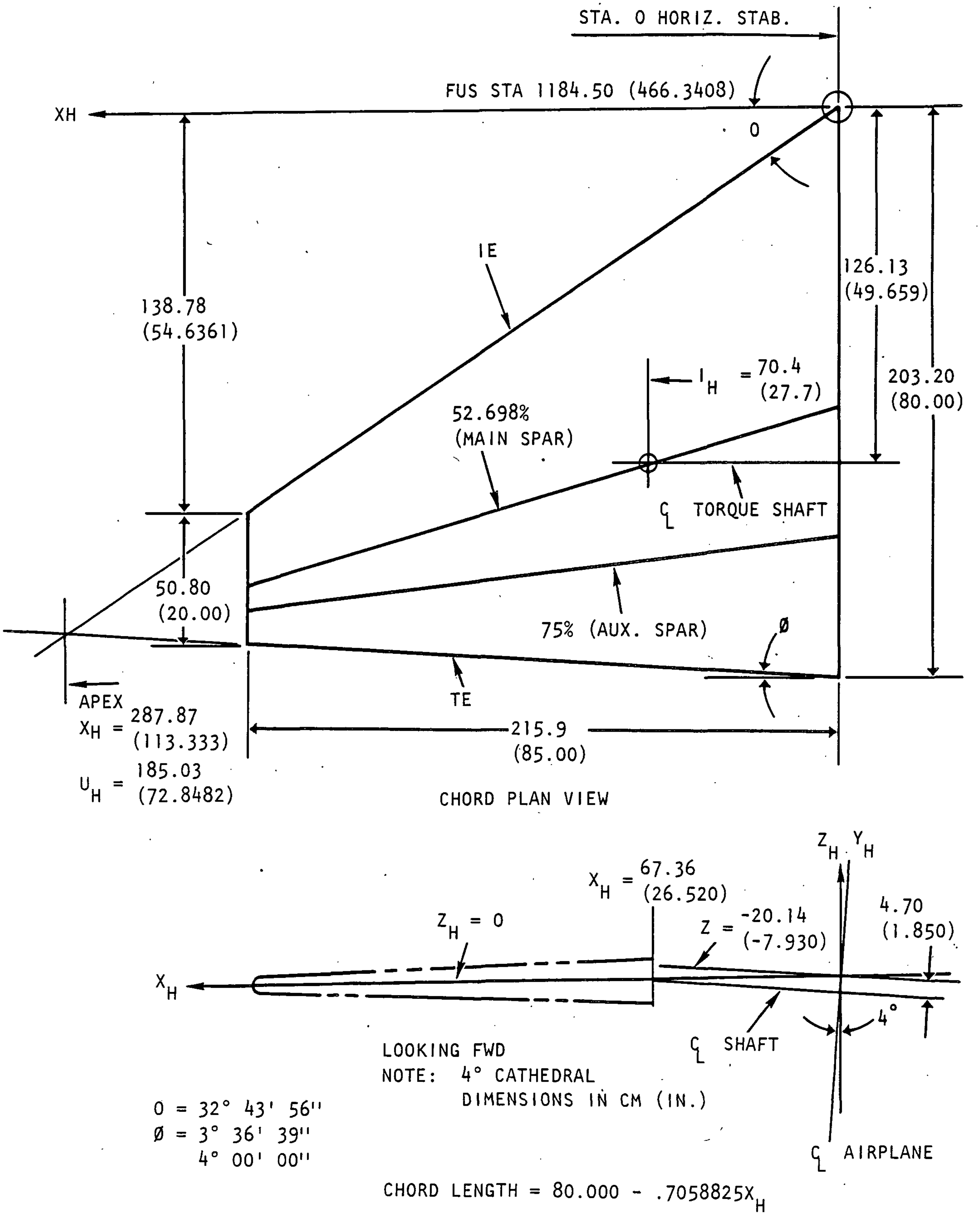


Figure 3-1. Basic Dimensions

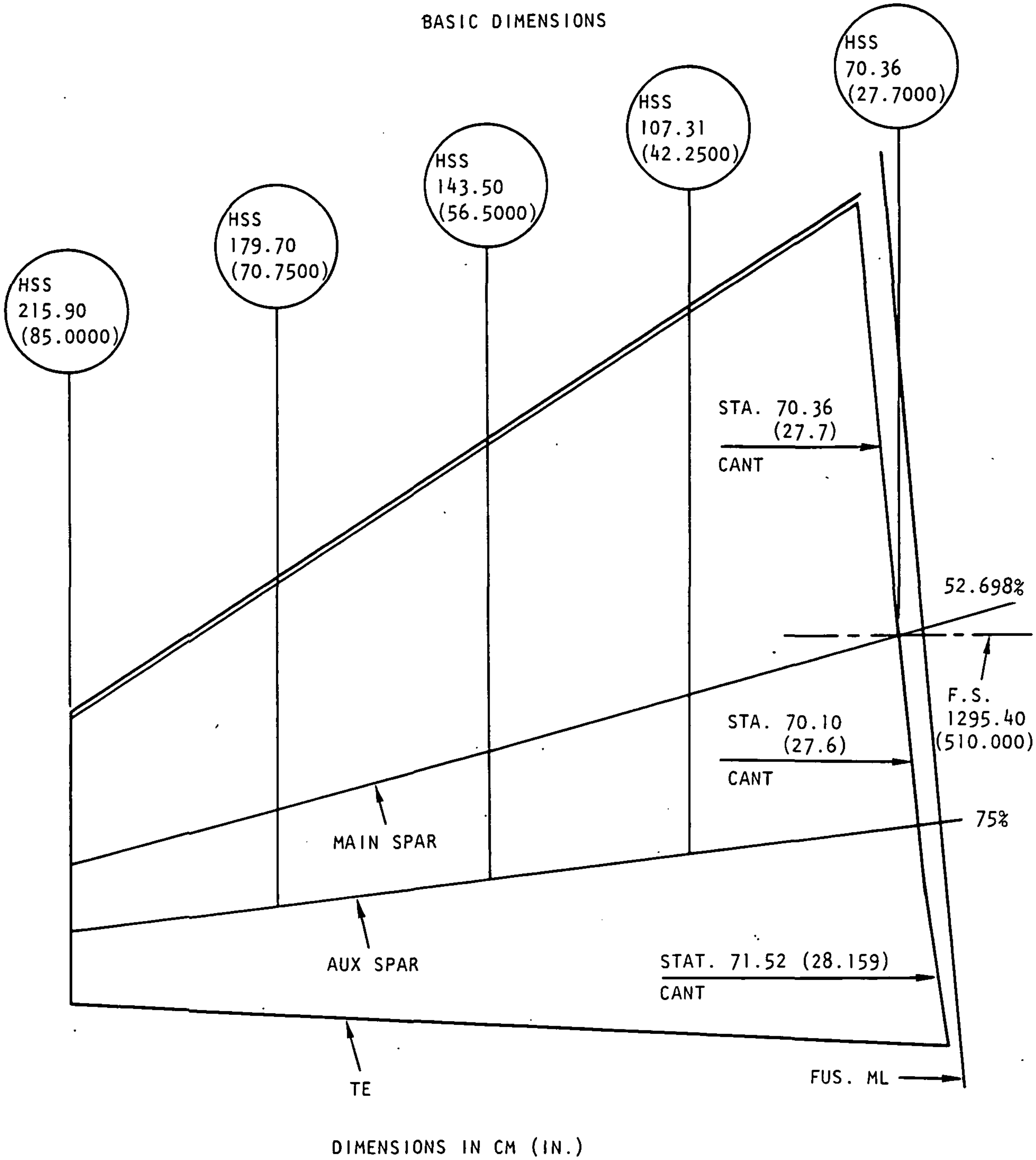


Figure 3-2. Stabilizer Reference Stations

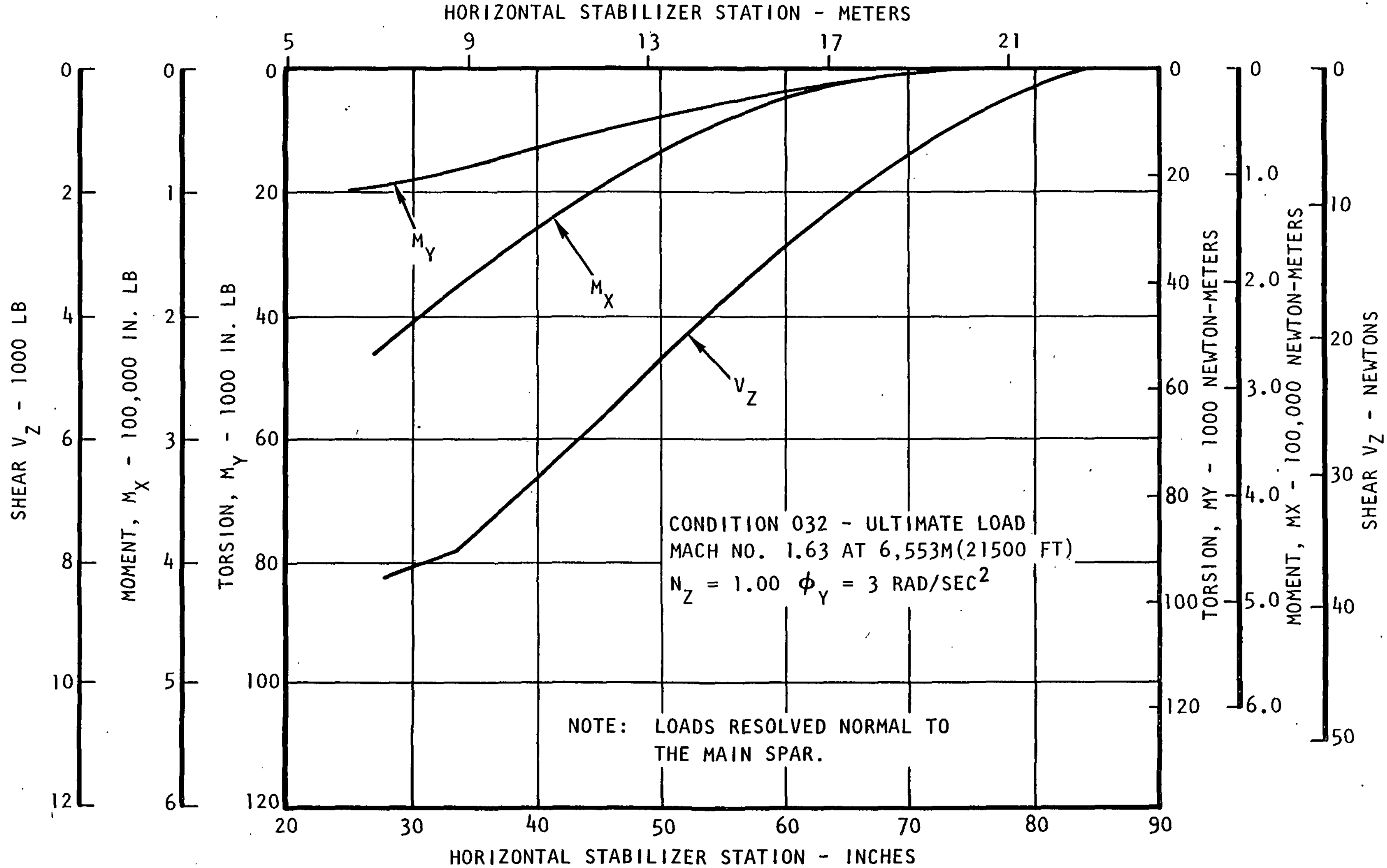


Figure 3-3. Horizontal Stabilizer Critical Supersonic Loading Conditions

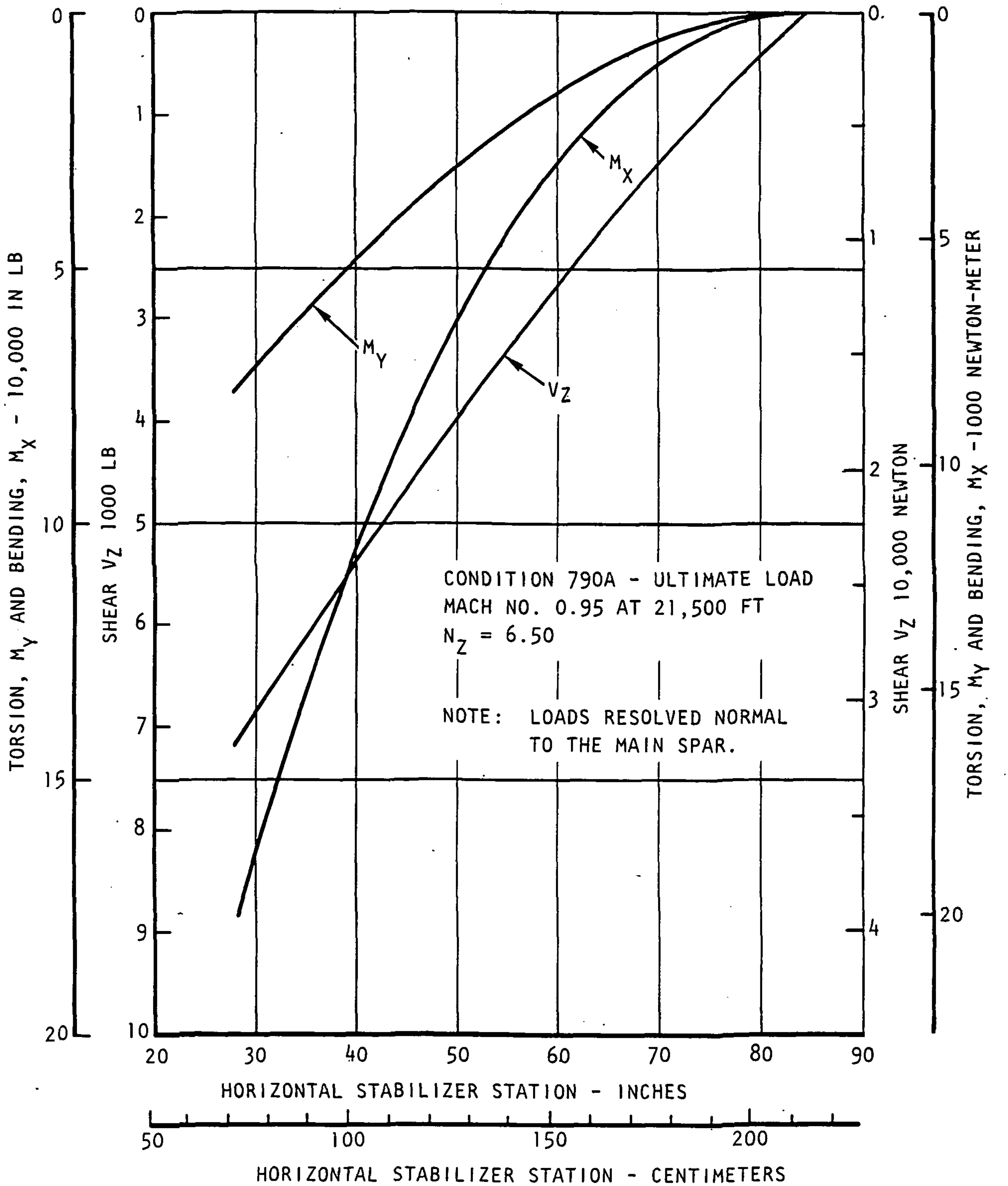


Figure 3-4. Horizontal Stabilizer Critical Subsonic Loading Condition

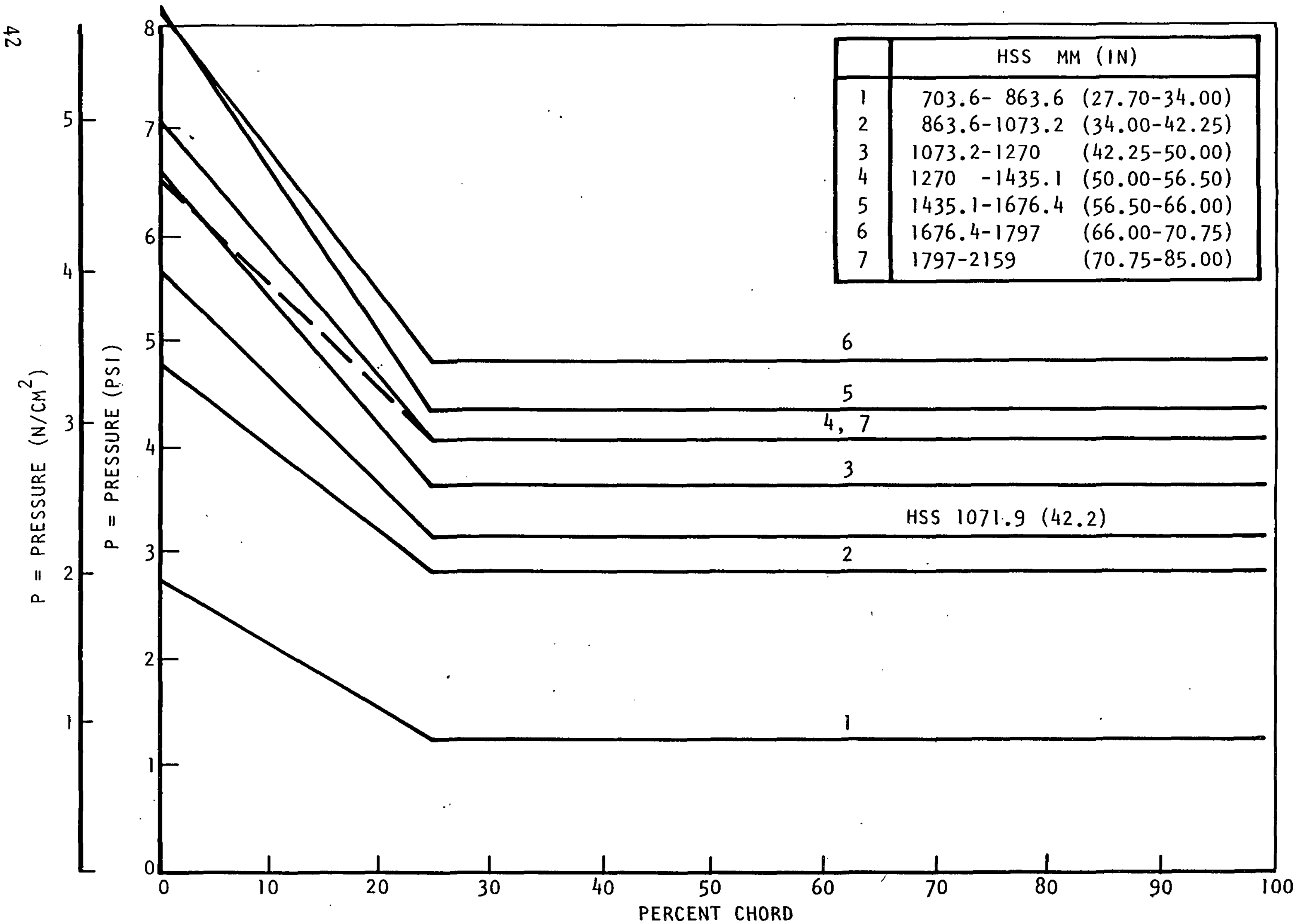


Figure 3-5. Chordwise Pressure Distribution

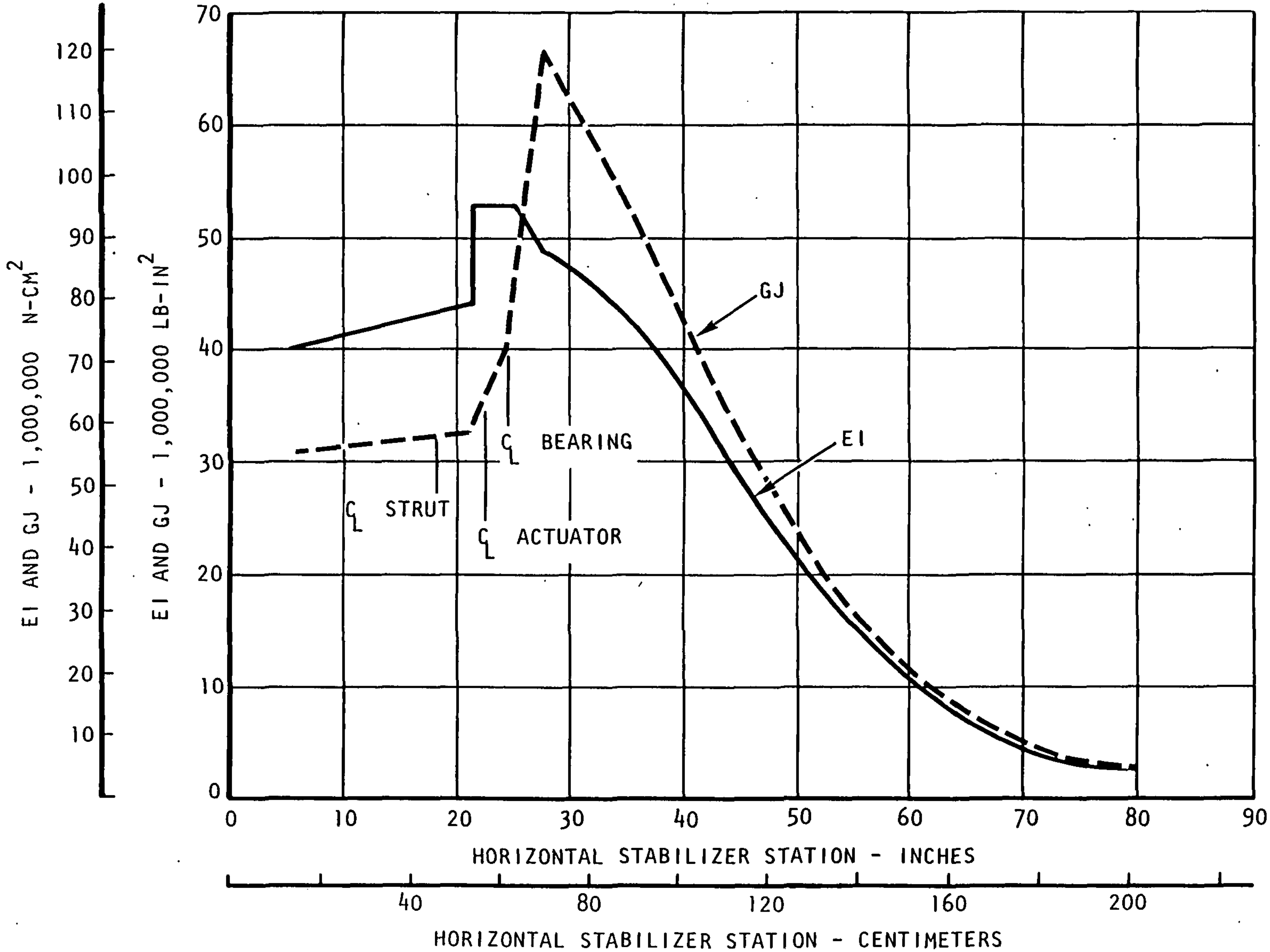


Figure 3-6. Horizontal Stabilizer Bending and Torsional Stiffness

NA-81-649

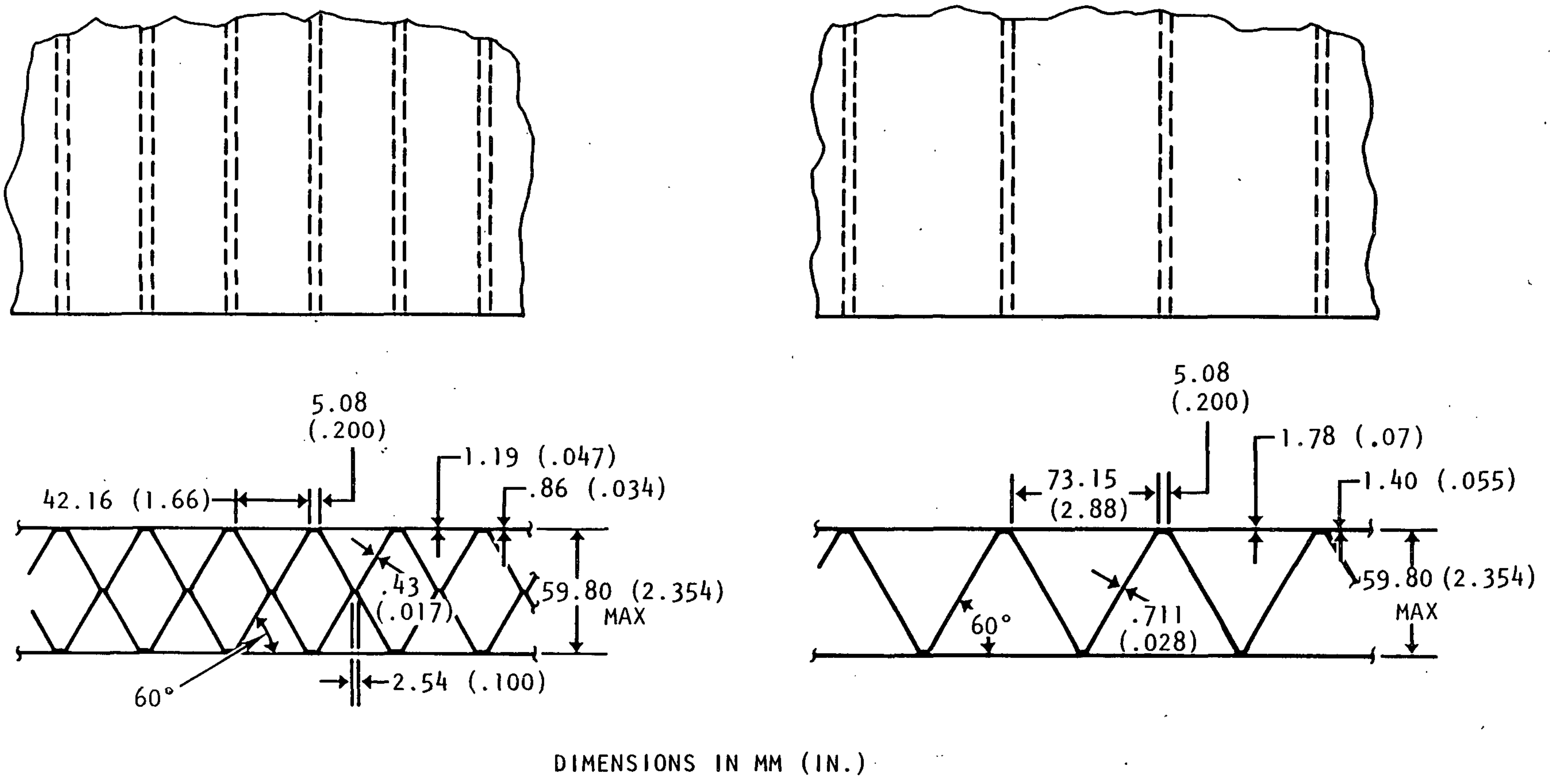
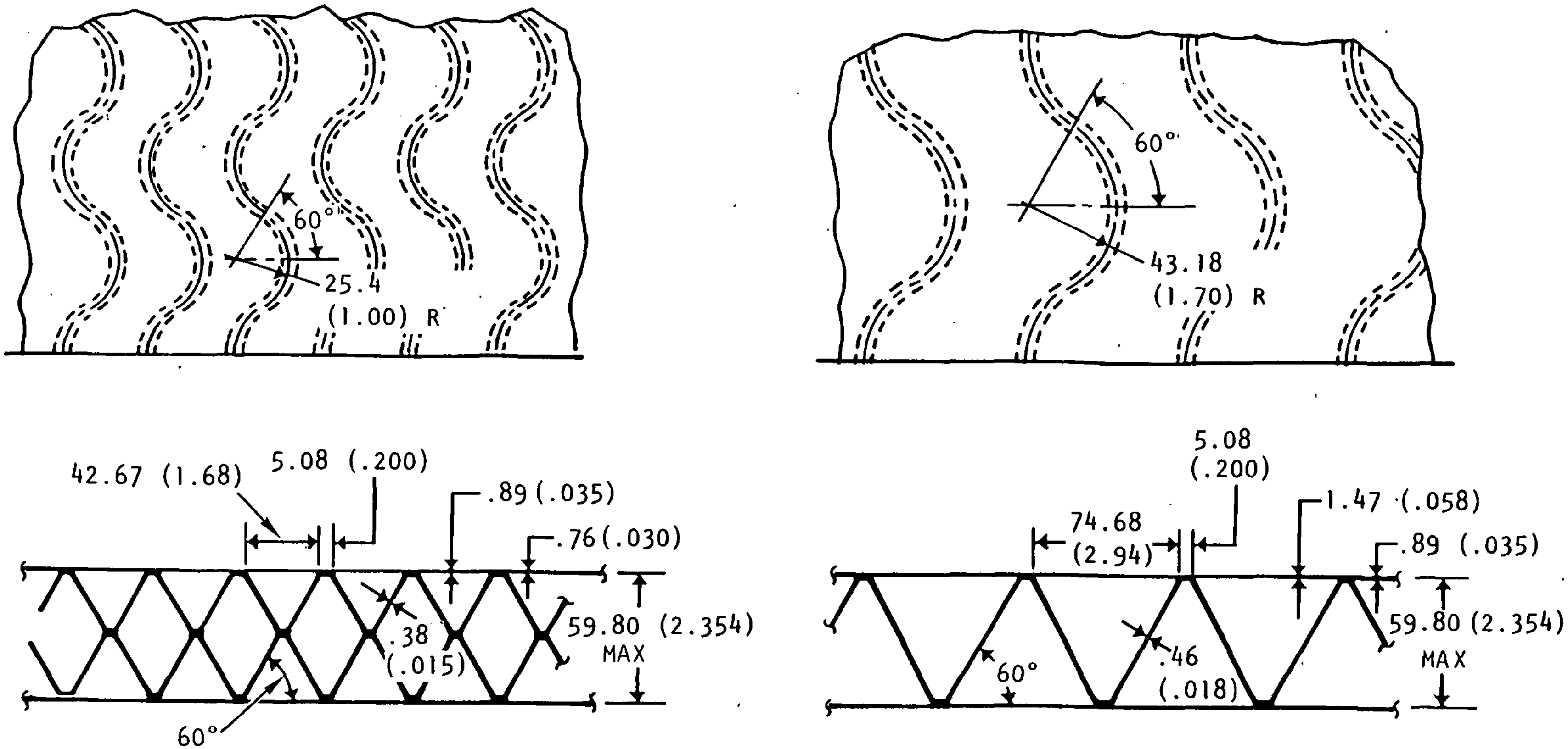


Figure 3-7. Straight Truss Core



DIMENSIONS IN MM (IN.)

Figure 3-8. Sine Wave Truss Core

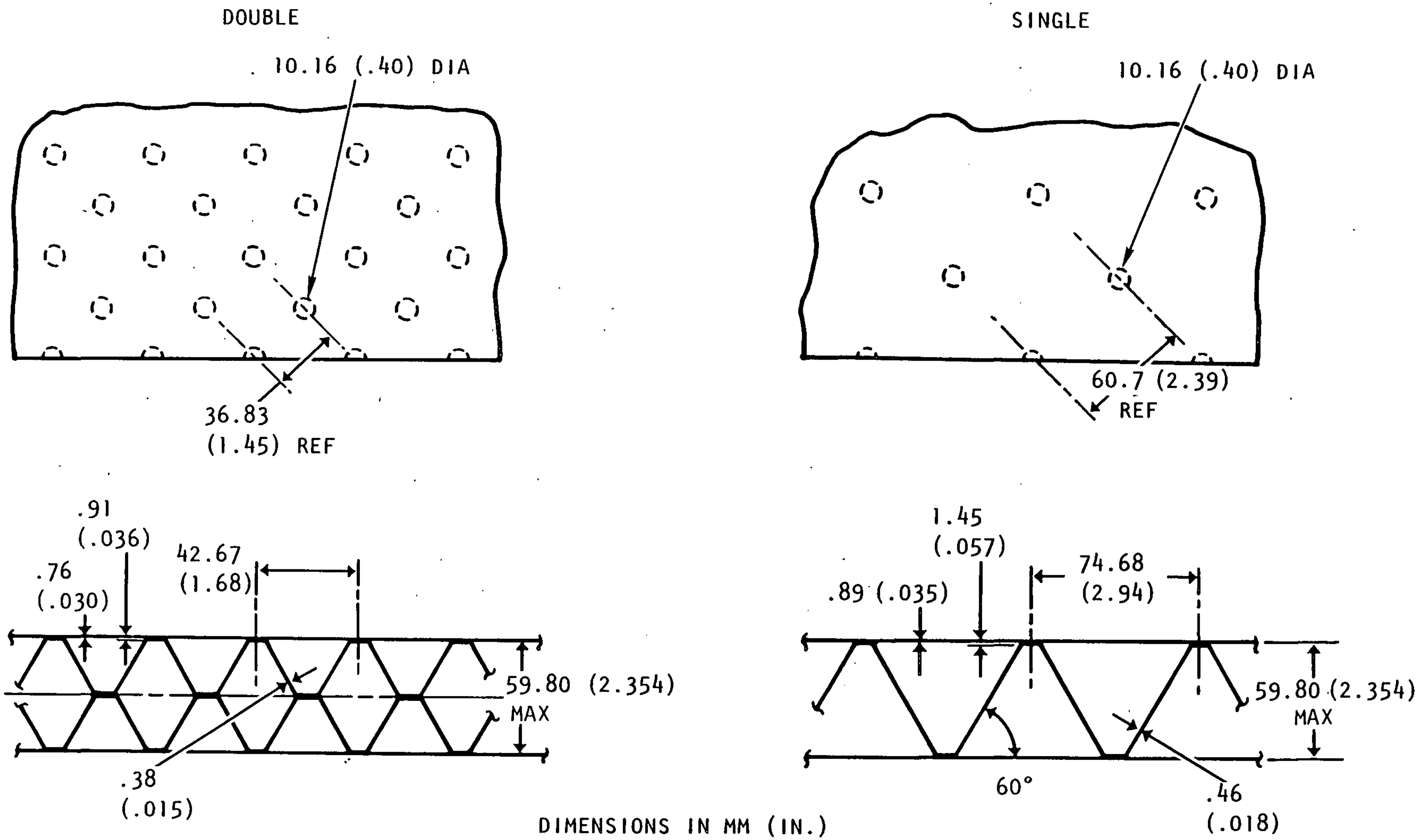


Figure 3-9. Dimple Core

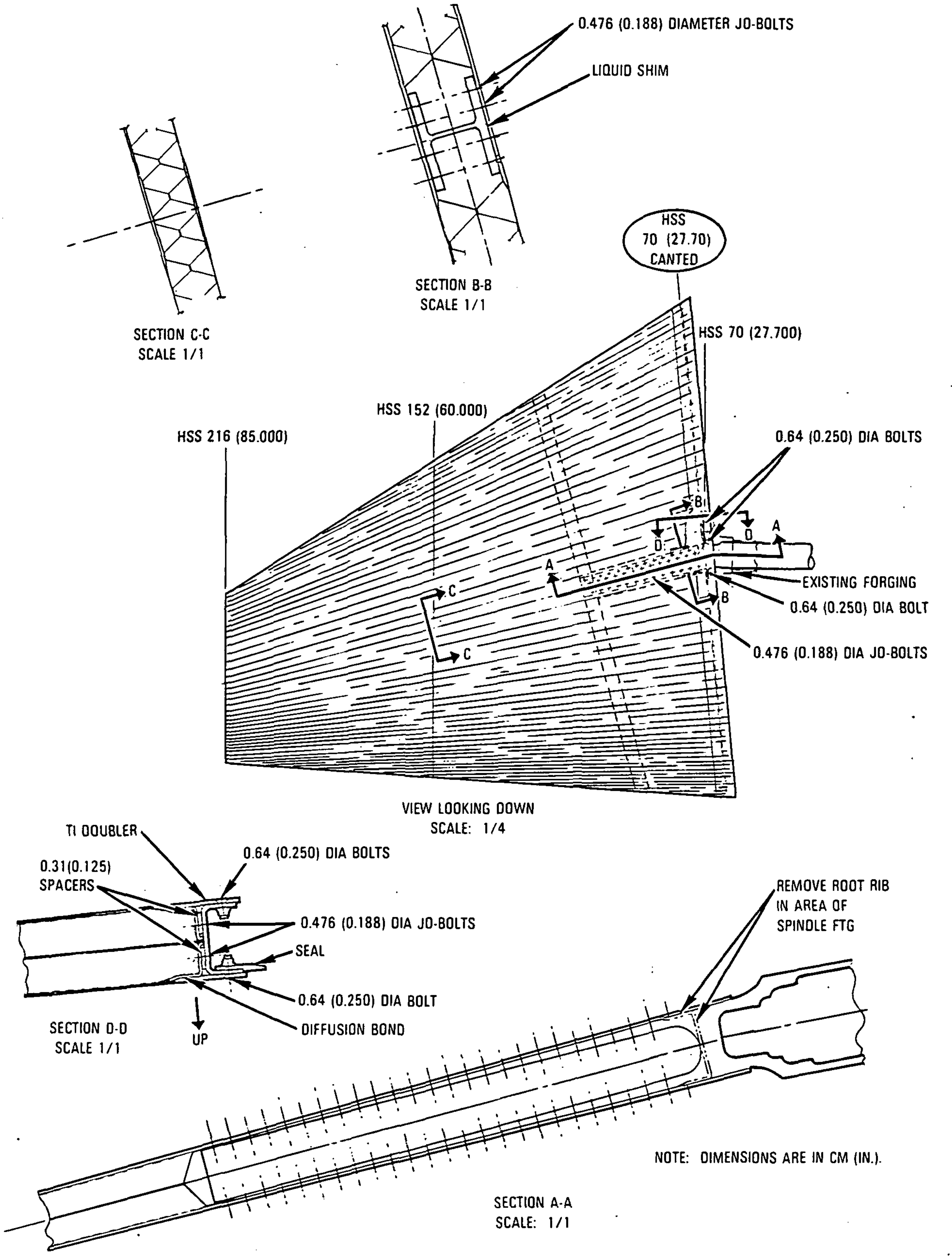


Figure 3-10. Concept A

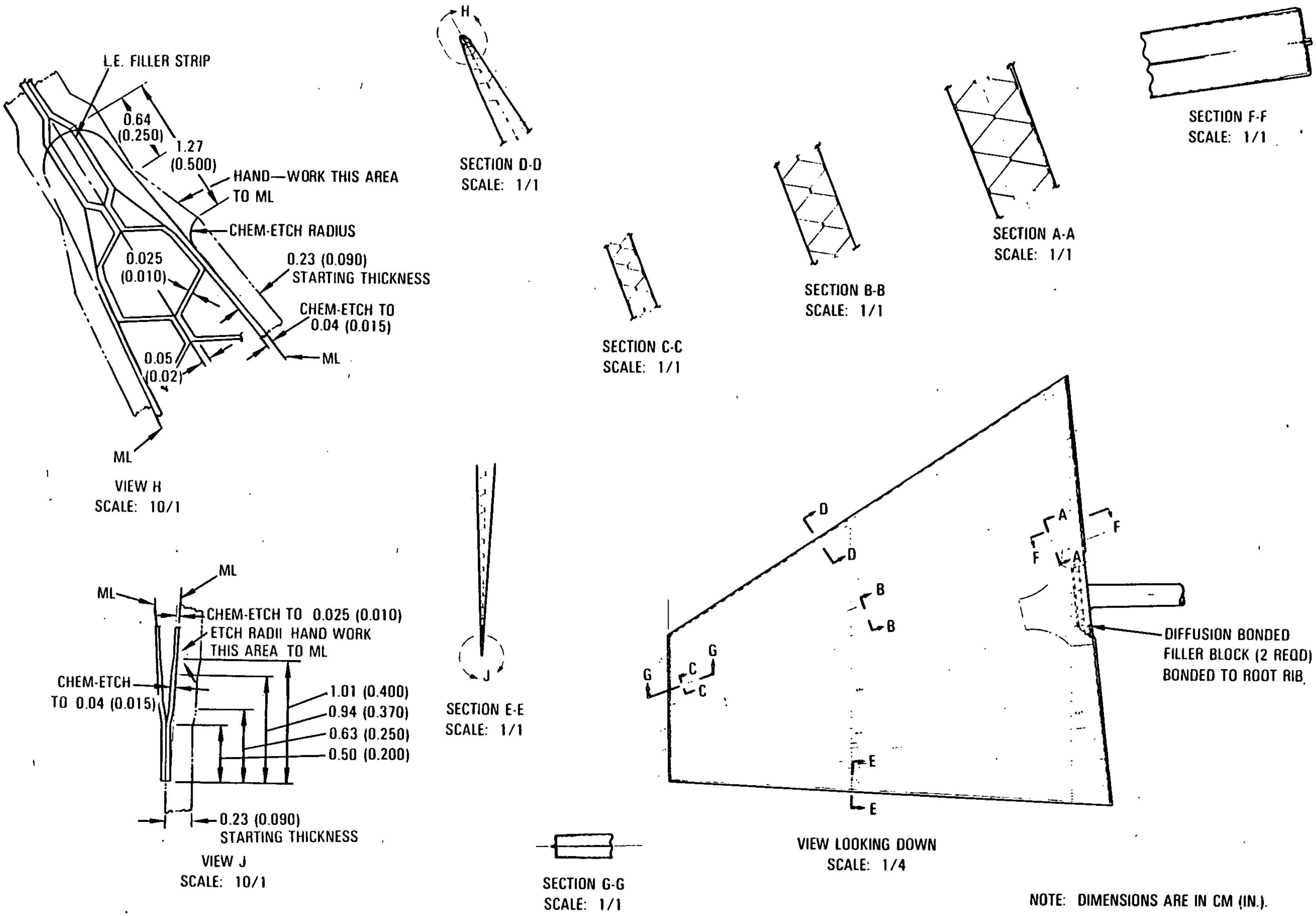


Figure 3-11. Concept B

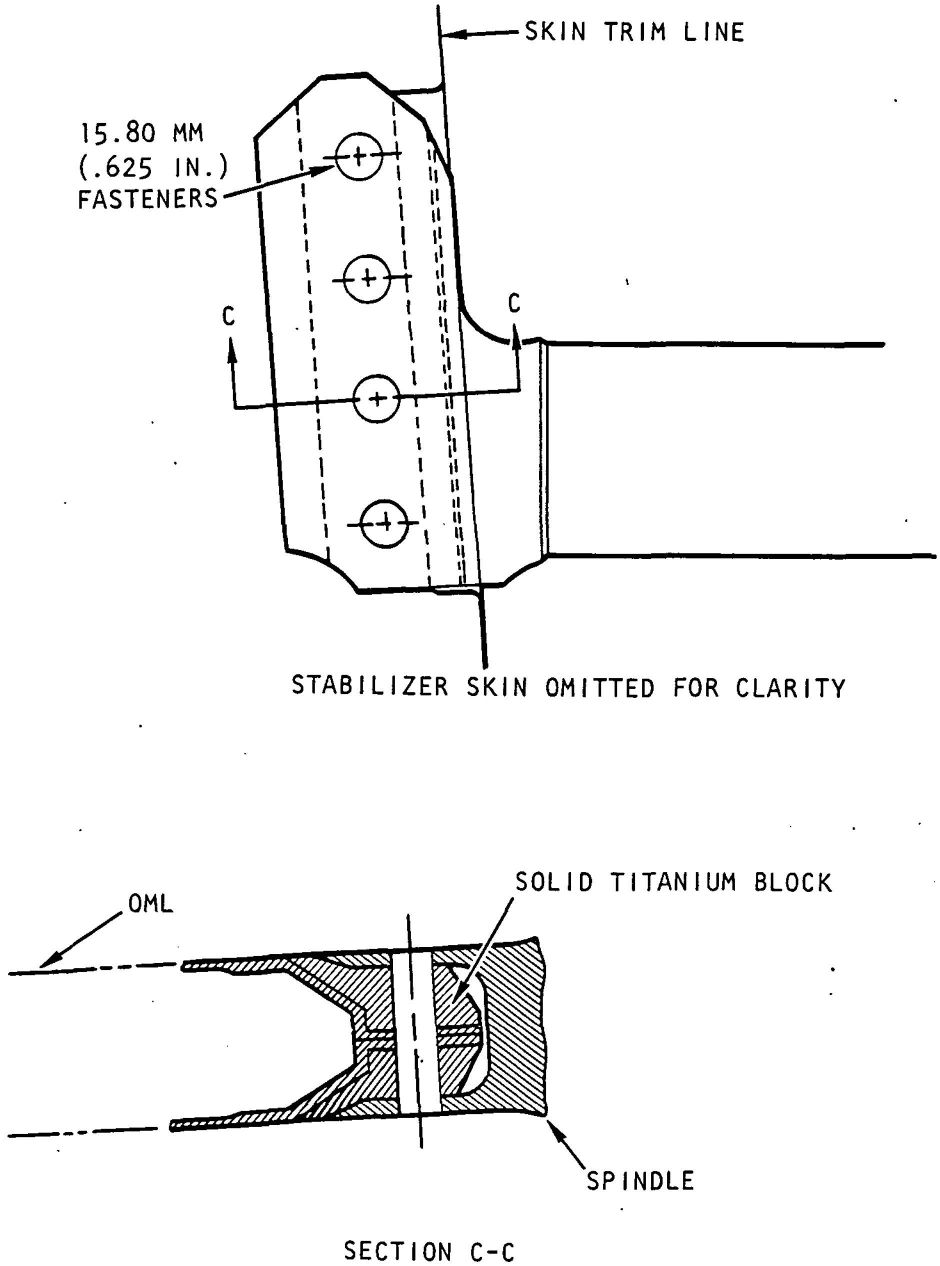


Figure 3-12. Spindle Concept I

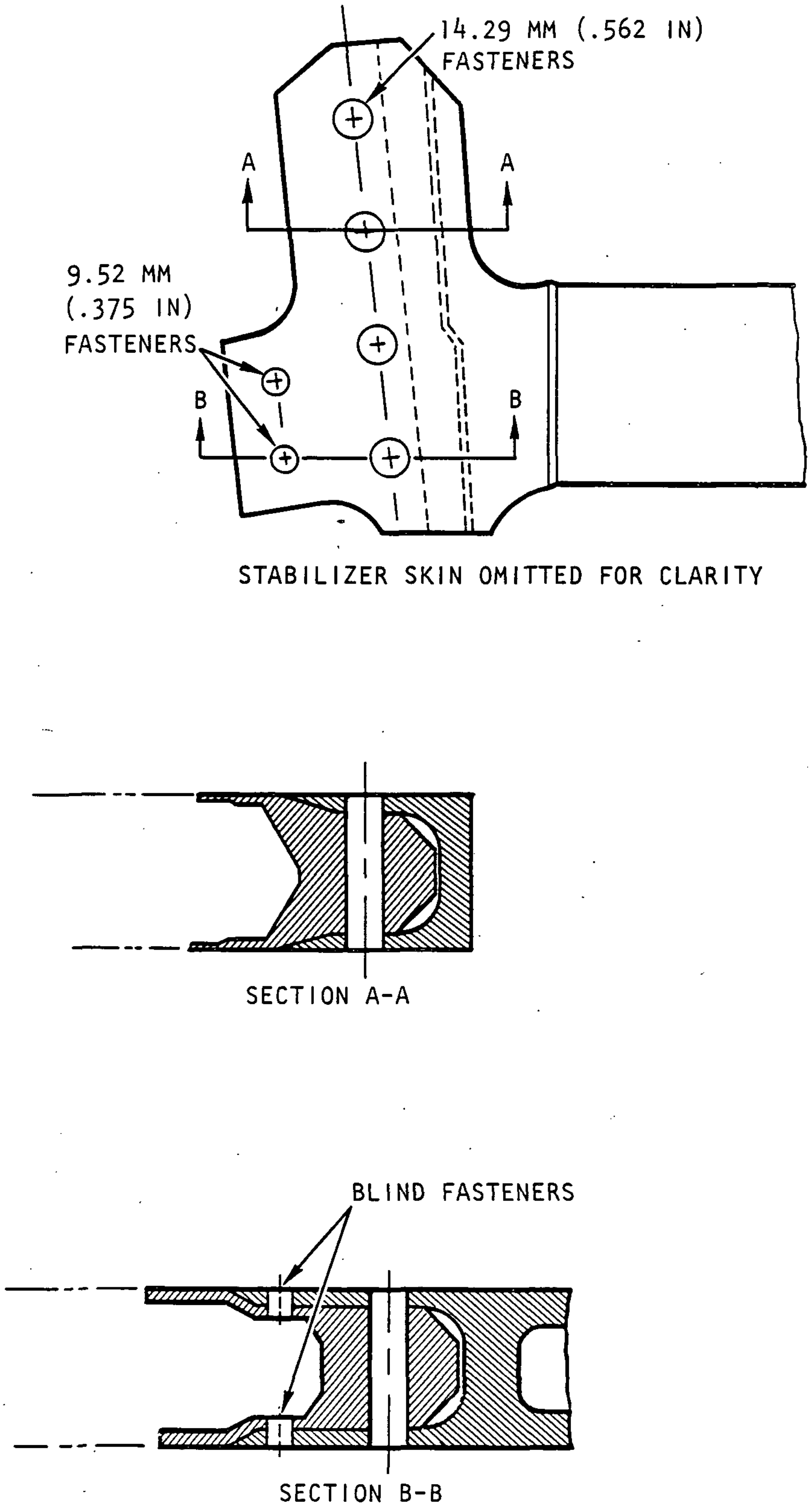
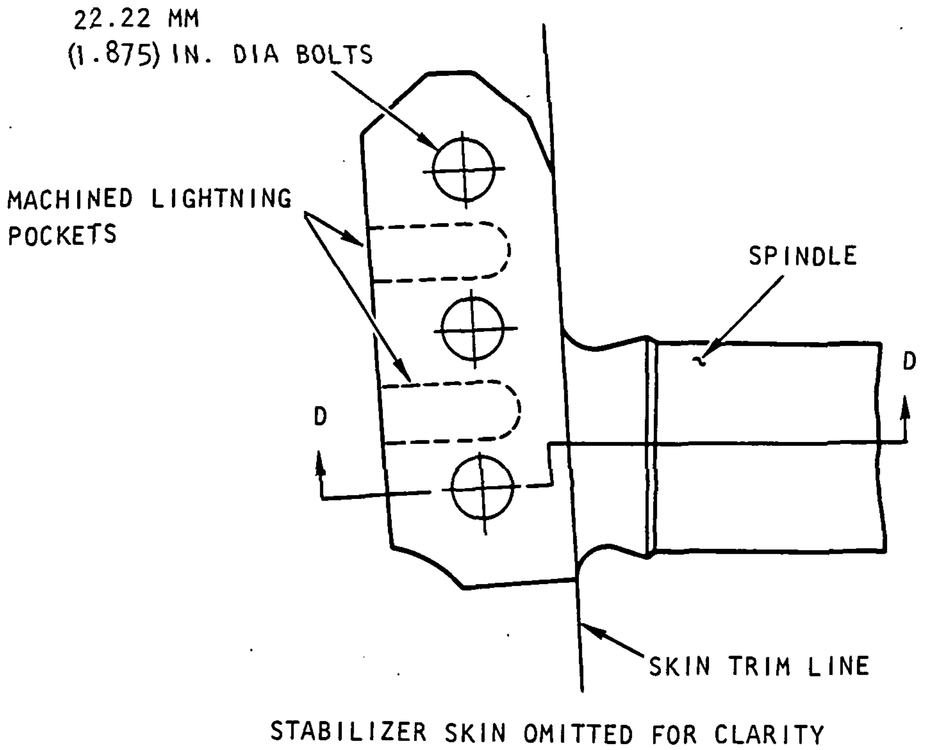


Figure 3-13. Spindle Concept II



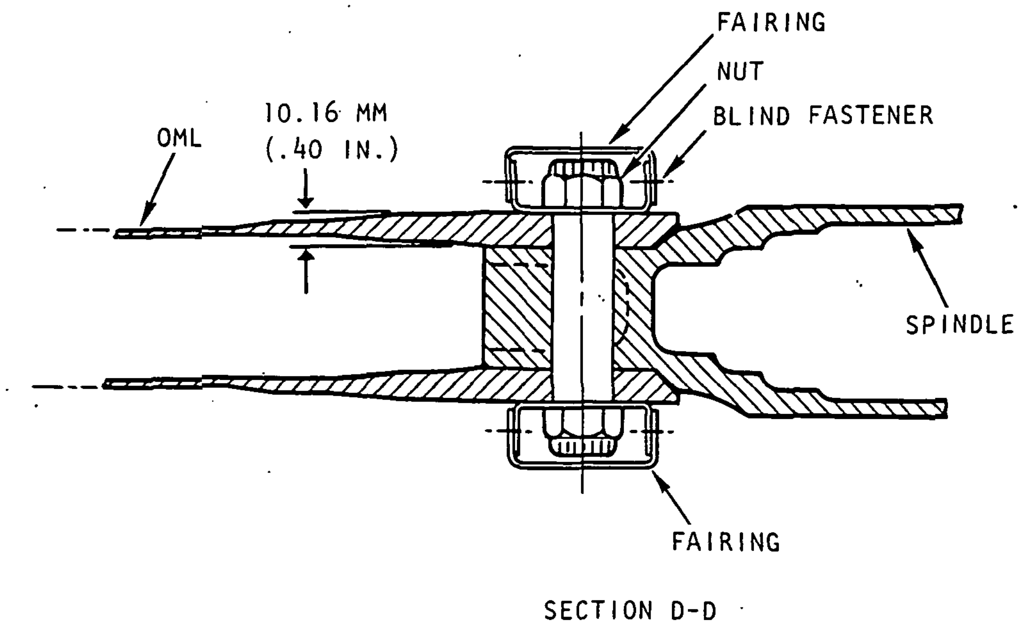


Figure 3-14. Spindle Concept III

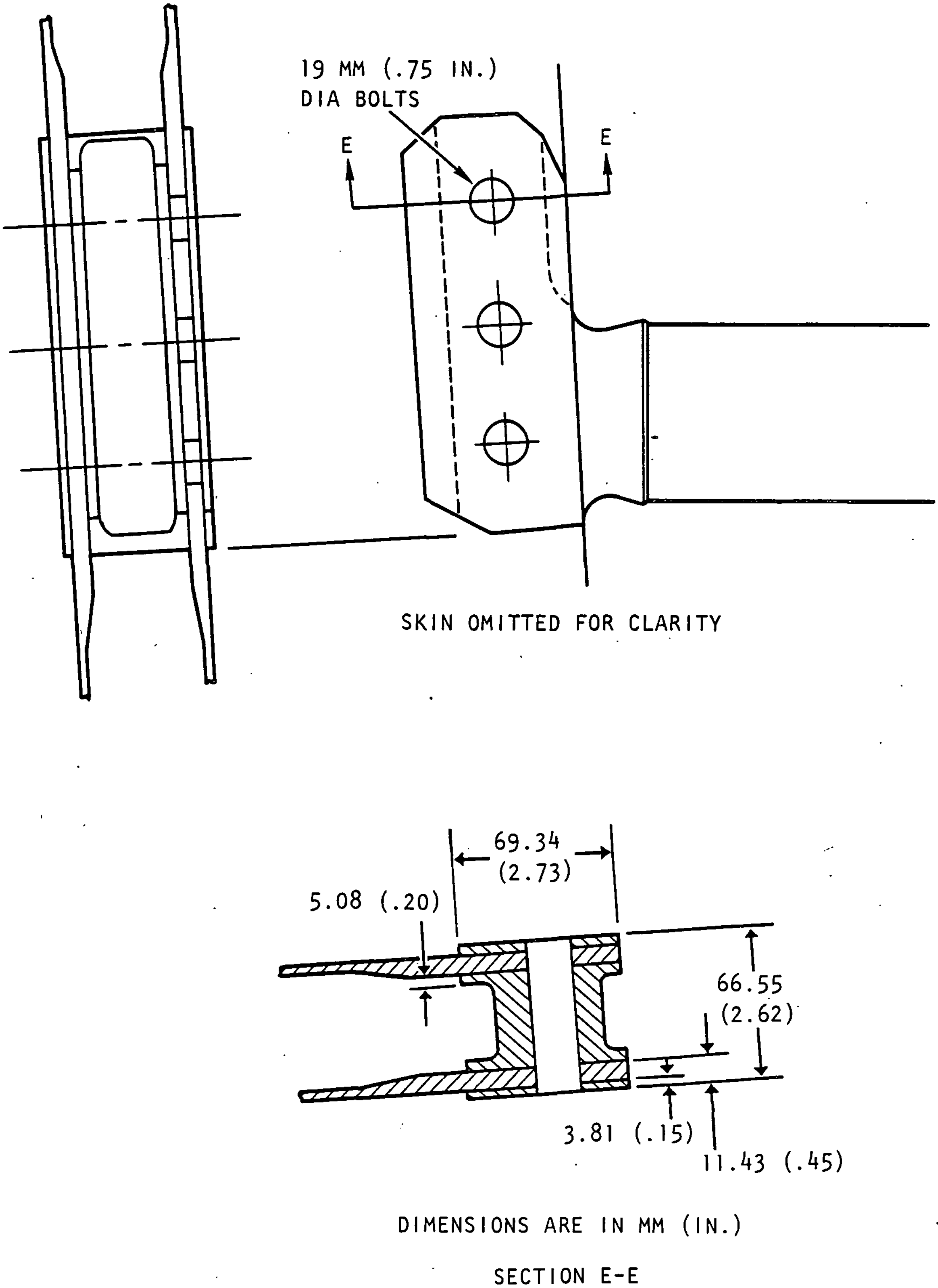


Figure 3-15. Spindle Concept IV

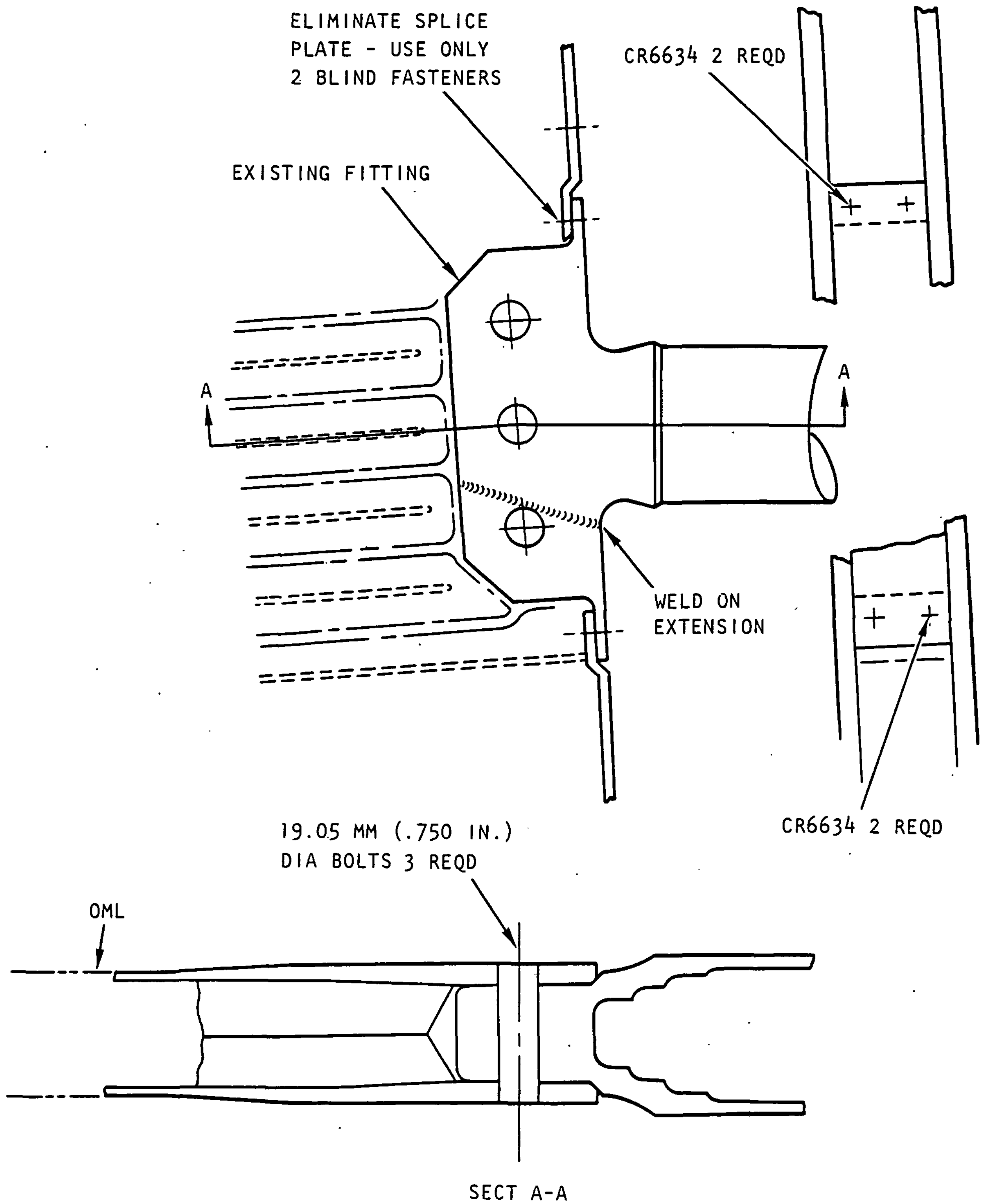
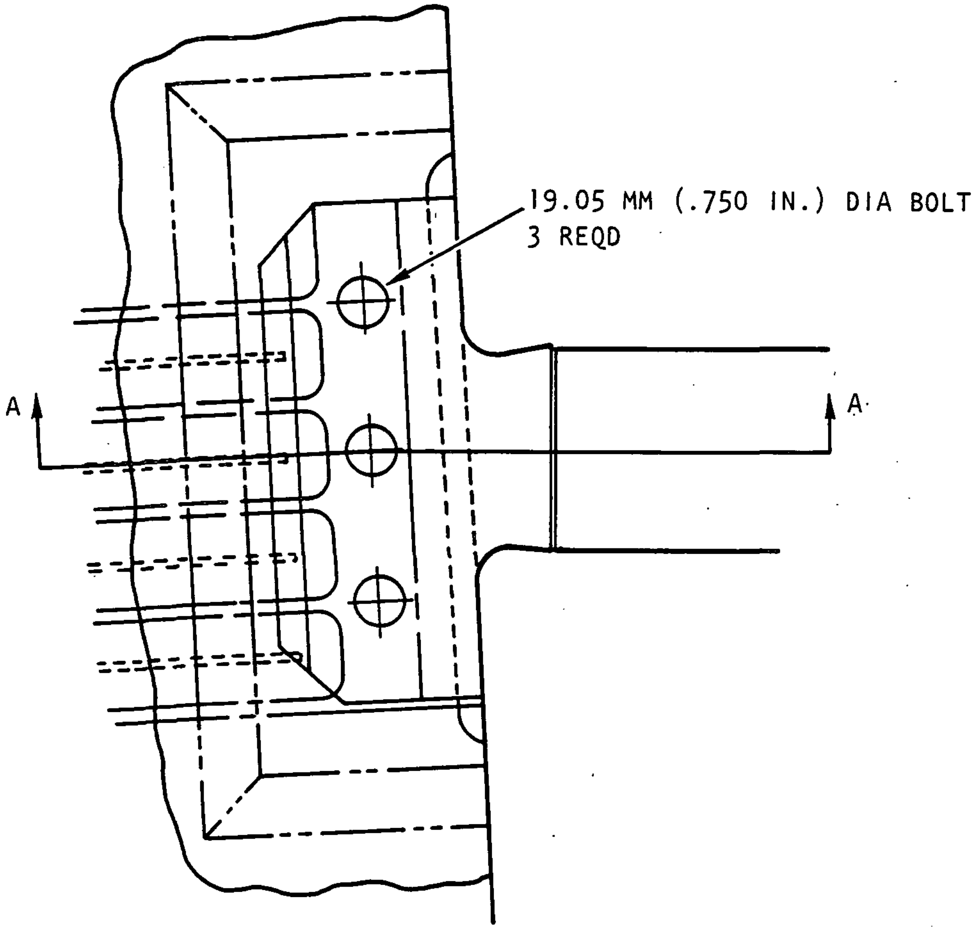


Figure 3-16. Spindle Concept V



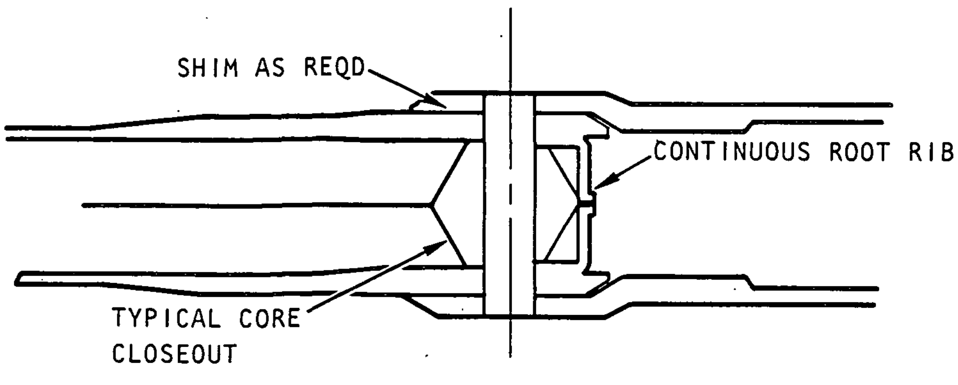


Figure 3-17. Spindle Concept VI

Figure 3-18. Spindle, Concepts VII and VIII

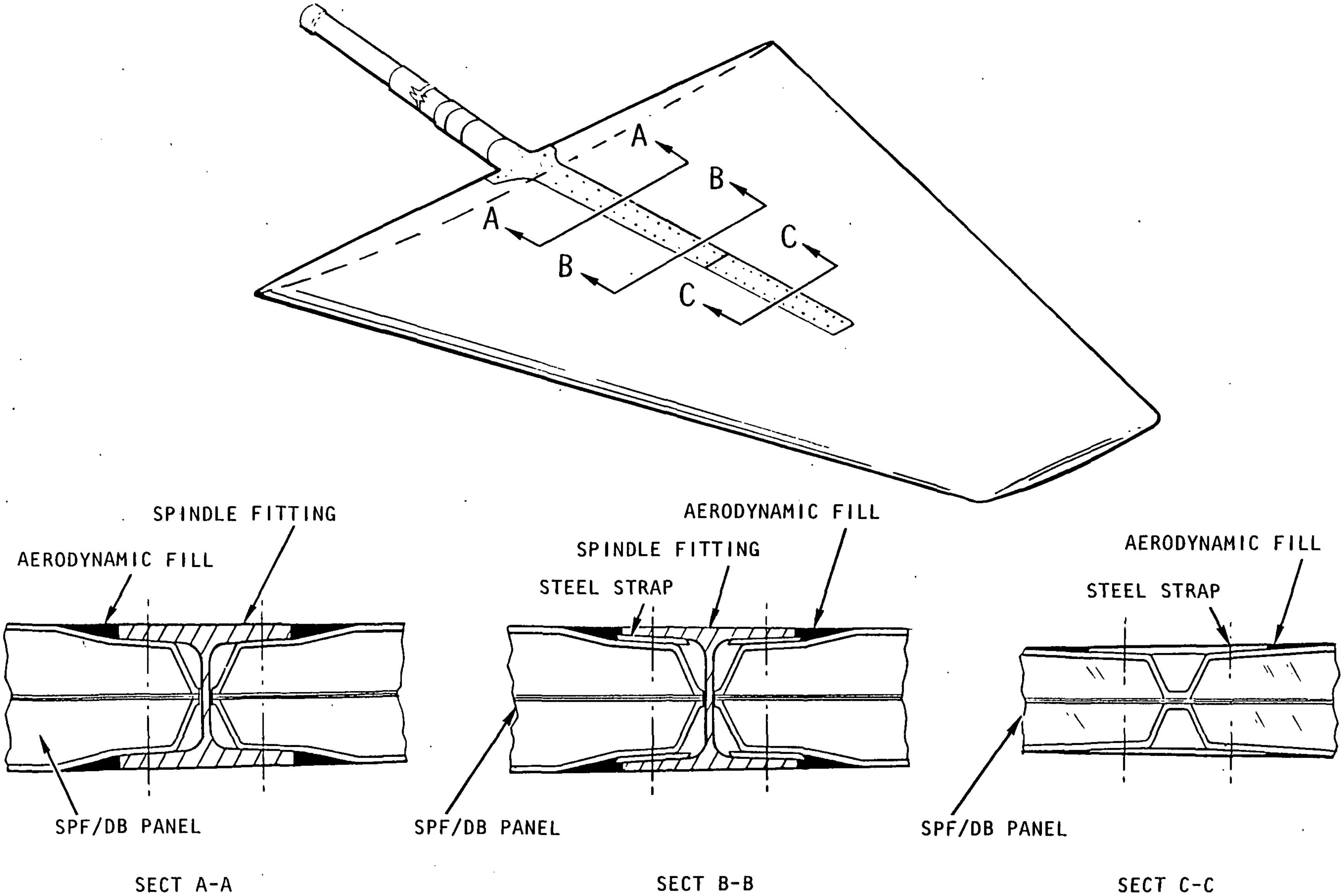
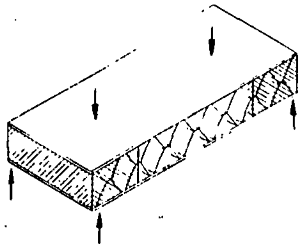
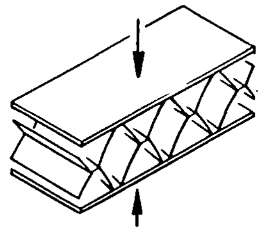


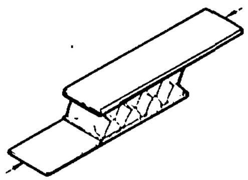
Figure 3-19. Selected Concept



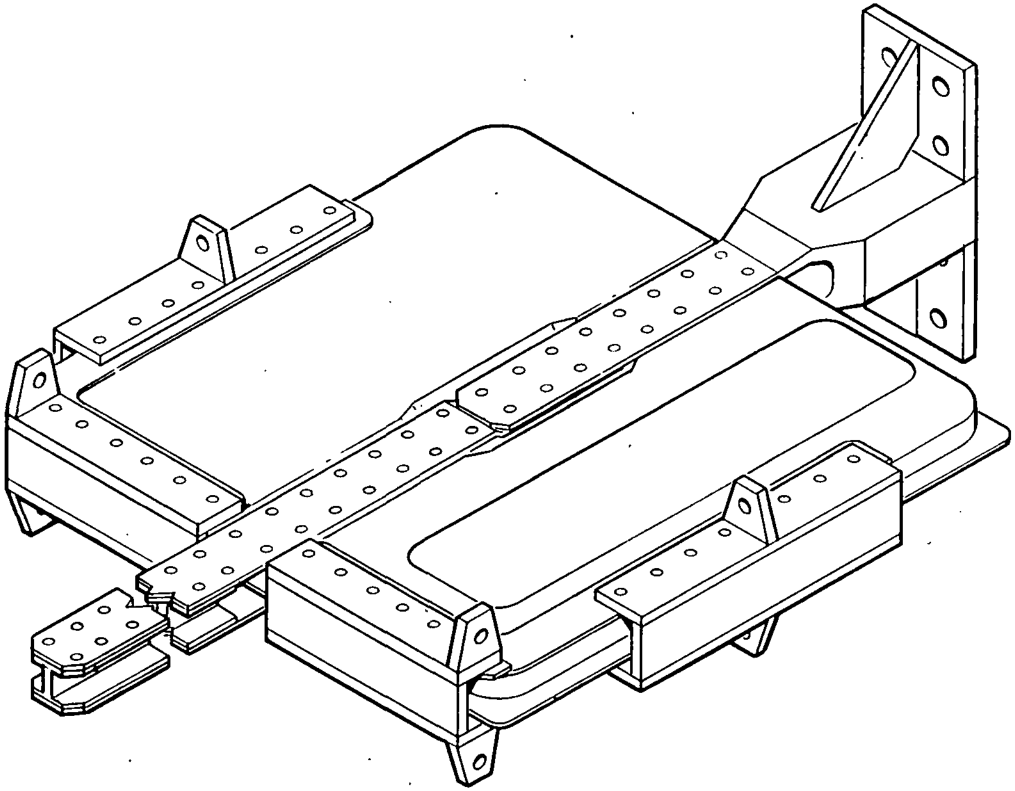
BENDING BEAM



FLATWISE COMPRESSION

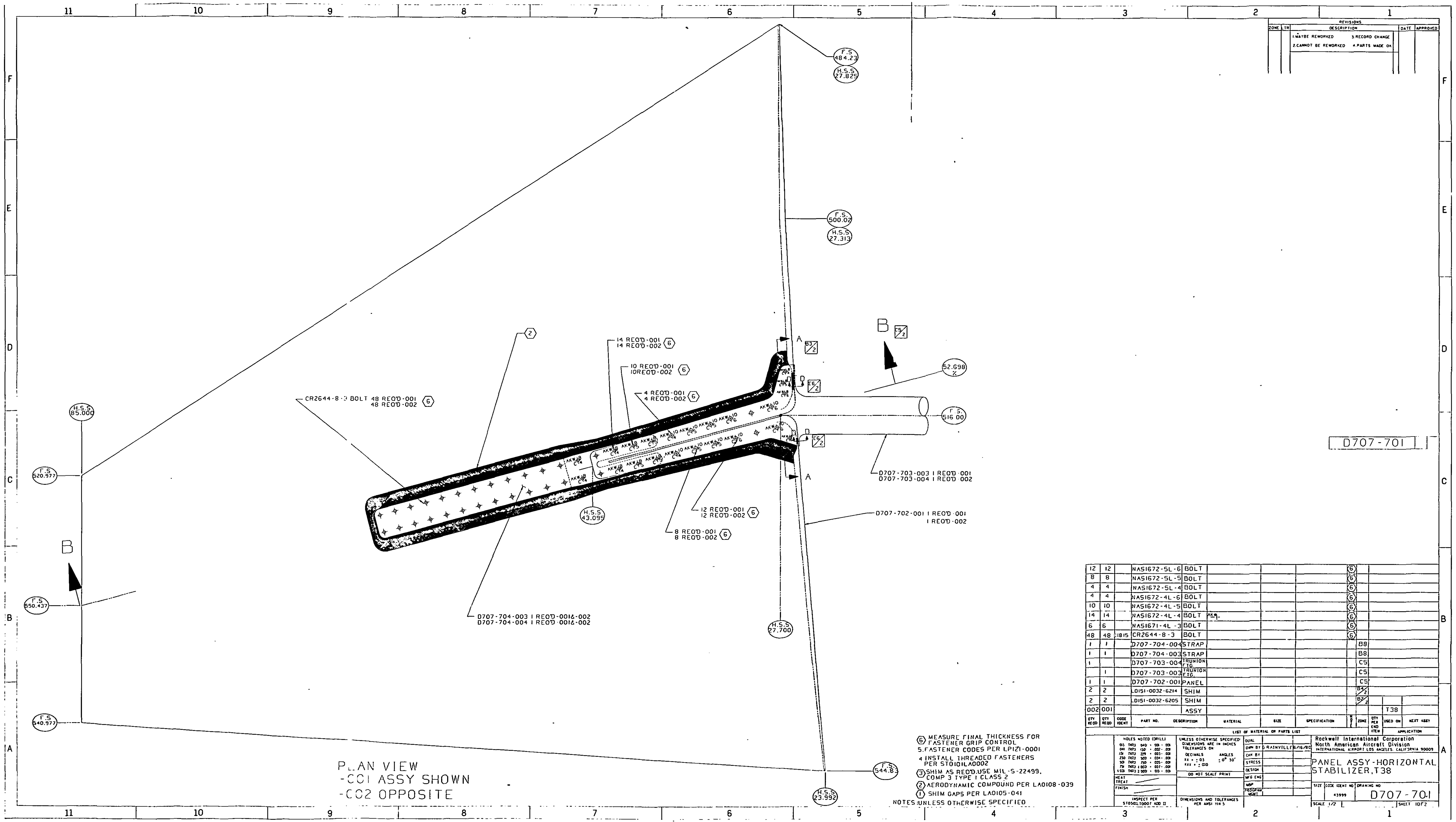


CORE SHEAR



JOINT TEST SPECIMEN

Figure 3-20. Development Test Specimens



QTY REQD	QTY REQD	CODE IDENT	PART NO.	DESCRIPTION	MATERIAL	SIZE	SPECIFICATION	NO.	ZONE	QTY PER END ITEM	USED ON	NEXT ASSY
12	12		NAS1672-5L-6	BOLT				6				
8	8		NAS1672-5L-5	BOLT				6				
4	4		NAS1672-5L-4	BOLT				6				
4	4		NAS1672-4L-6	BOLT				6				
10	10		NAS1672-4L-5	BOLT				6				
14	14		NAS1672-4L-4	BOLT	AKW1			6				
6	6		NAS1671-4L-3	BOLT				6				
48	48	81815	CR2644-8-3	BOLT				6				
1	1		D707-704-004	STRAP					B8			
1	1		D707-704-003	STRAP					B8			
1			D707-703-004	TRUNION FTG.					C5			
	1		D707-703-003	TRUNION FTG.					C5			
1	1		D707-702-001	PANEL					C5			
2	2		L0151-0032-6214	SHIM					B4/2			
2	2		L0151-0032-6205	SHIM					B2/2			
002	001			ASSY							T38	

LIST OF MATERIAL OR PARTS LIST

Figure 3-21. Horizontal Stabilizer Assembly

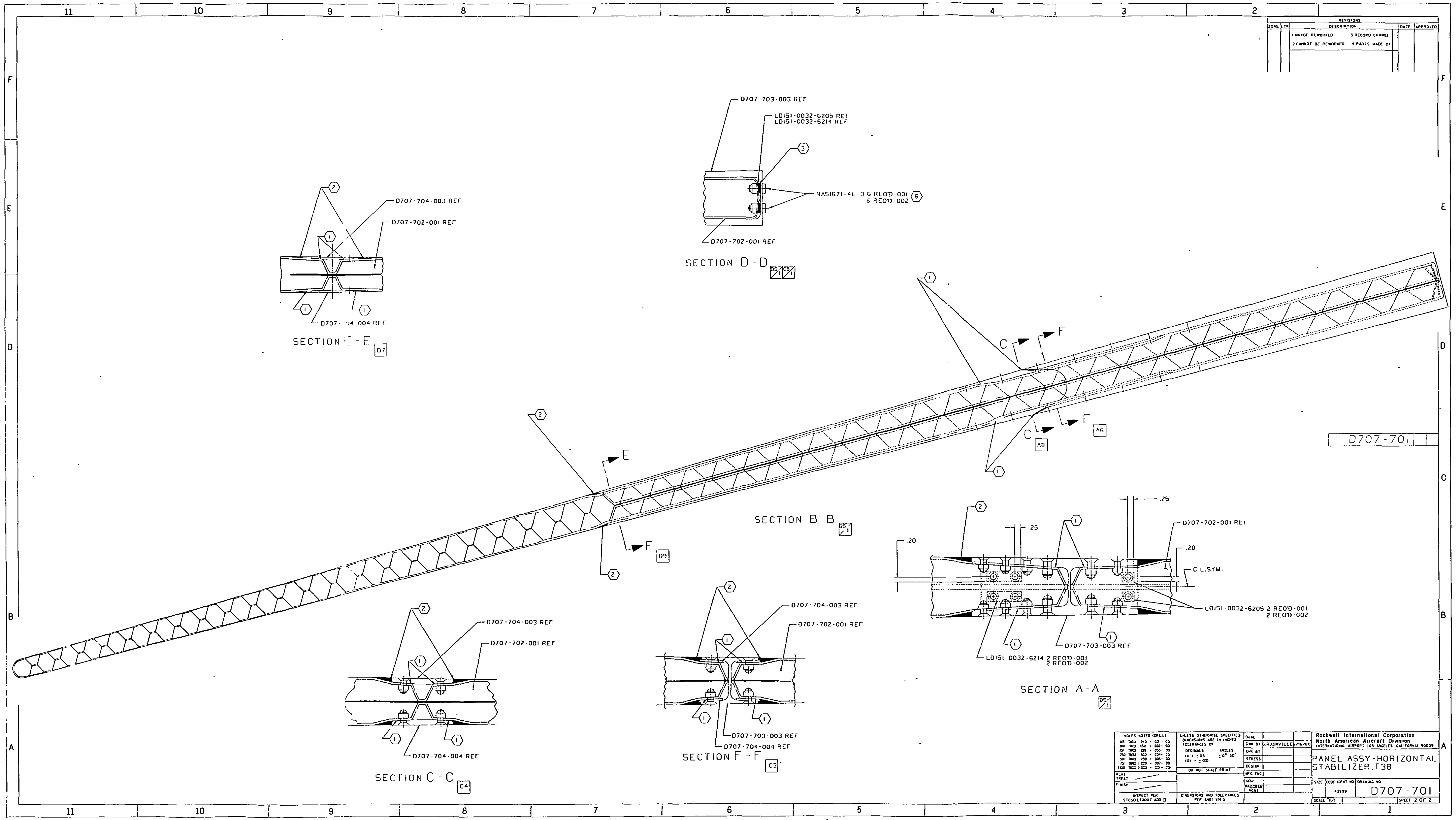


Figure 5-21. Horizontal Stabilizer Assembly (concl)

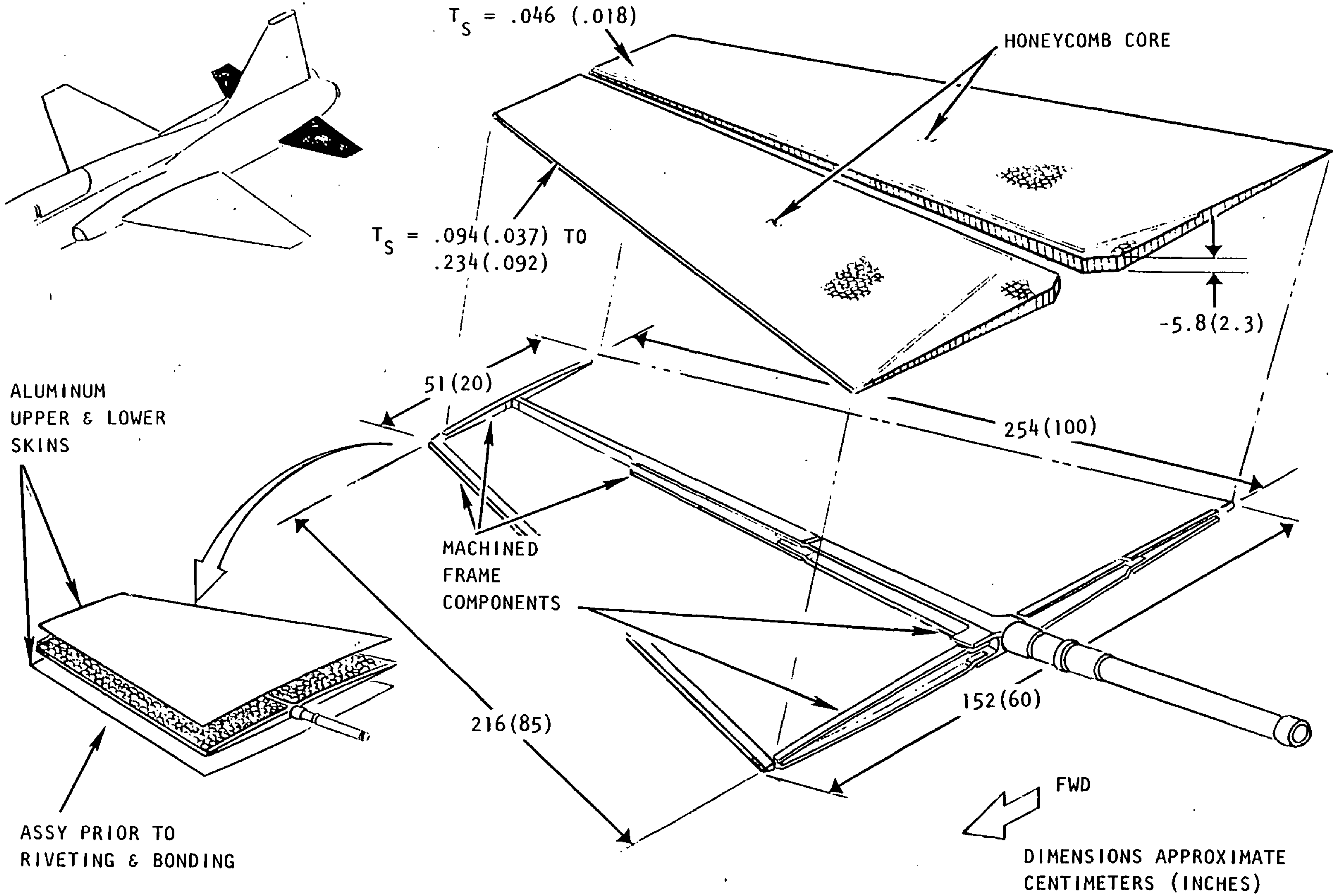


Figure 3-22. Existing T-38 Horizontal Stabilizer

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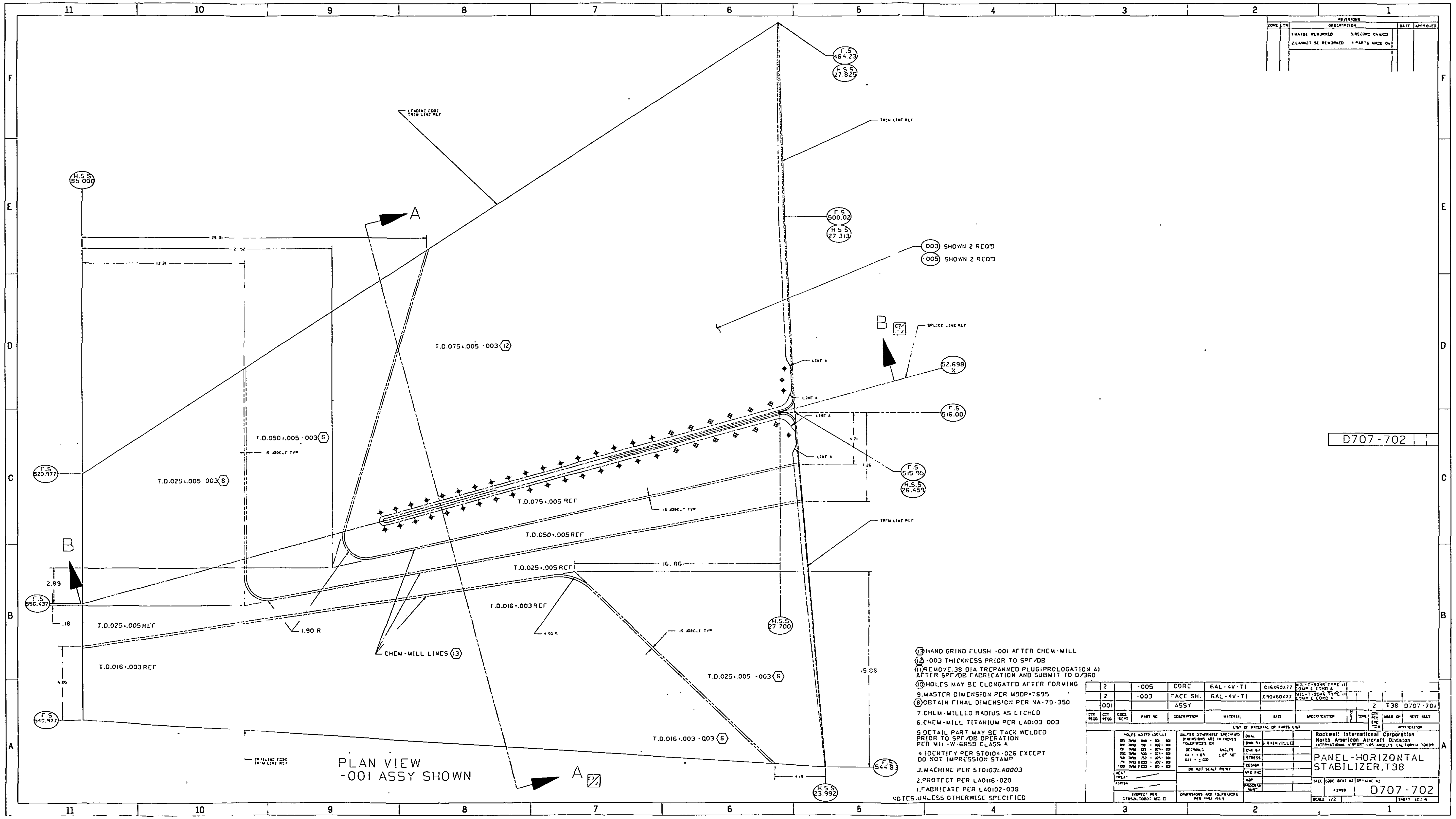


Figure 3-23. SPF/DB Horizontal Stabilizer Panel

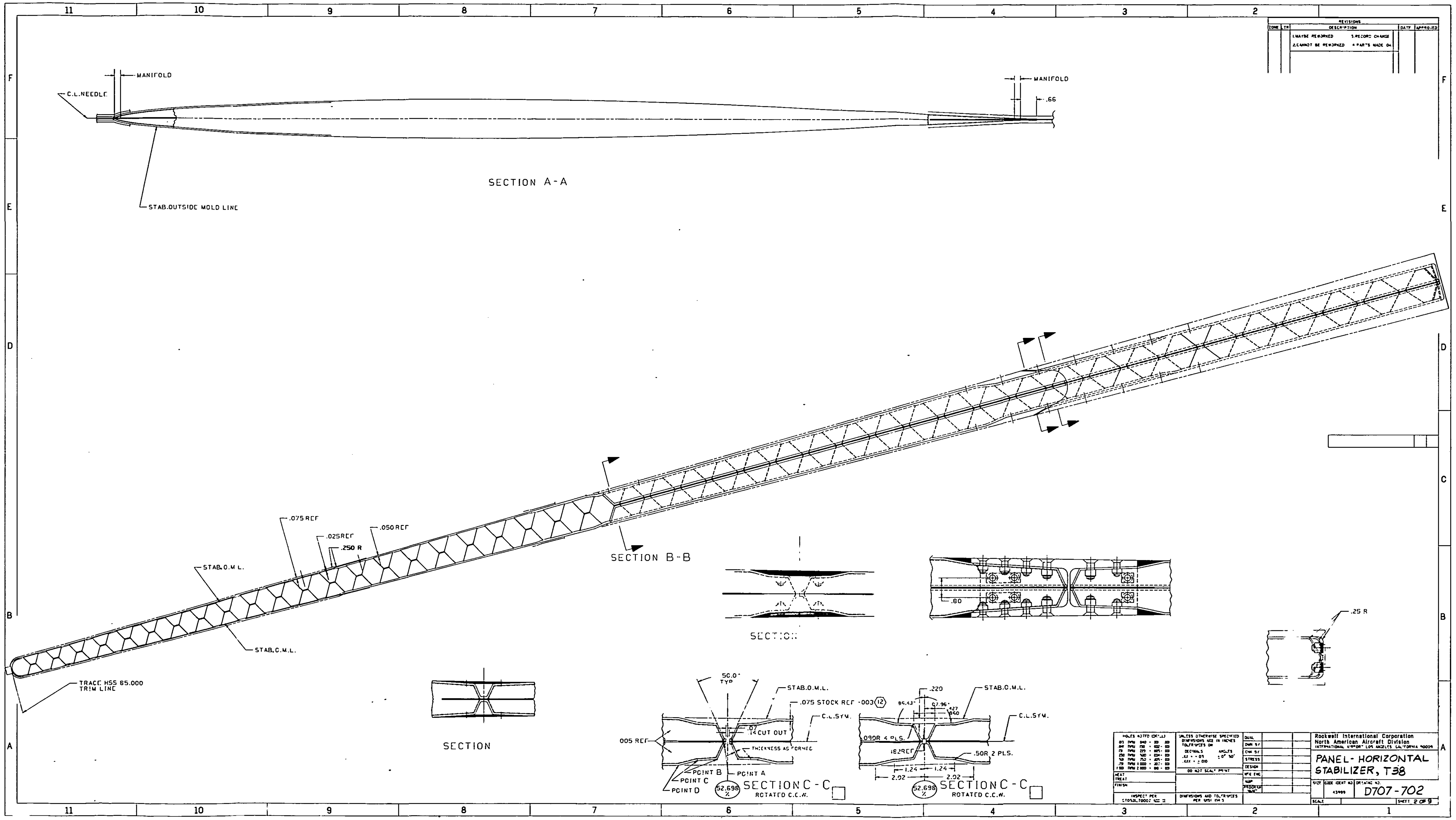


Figure 3-23 SPF/DB Horizontal Stabilizer Panel (cont)

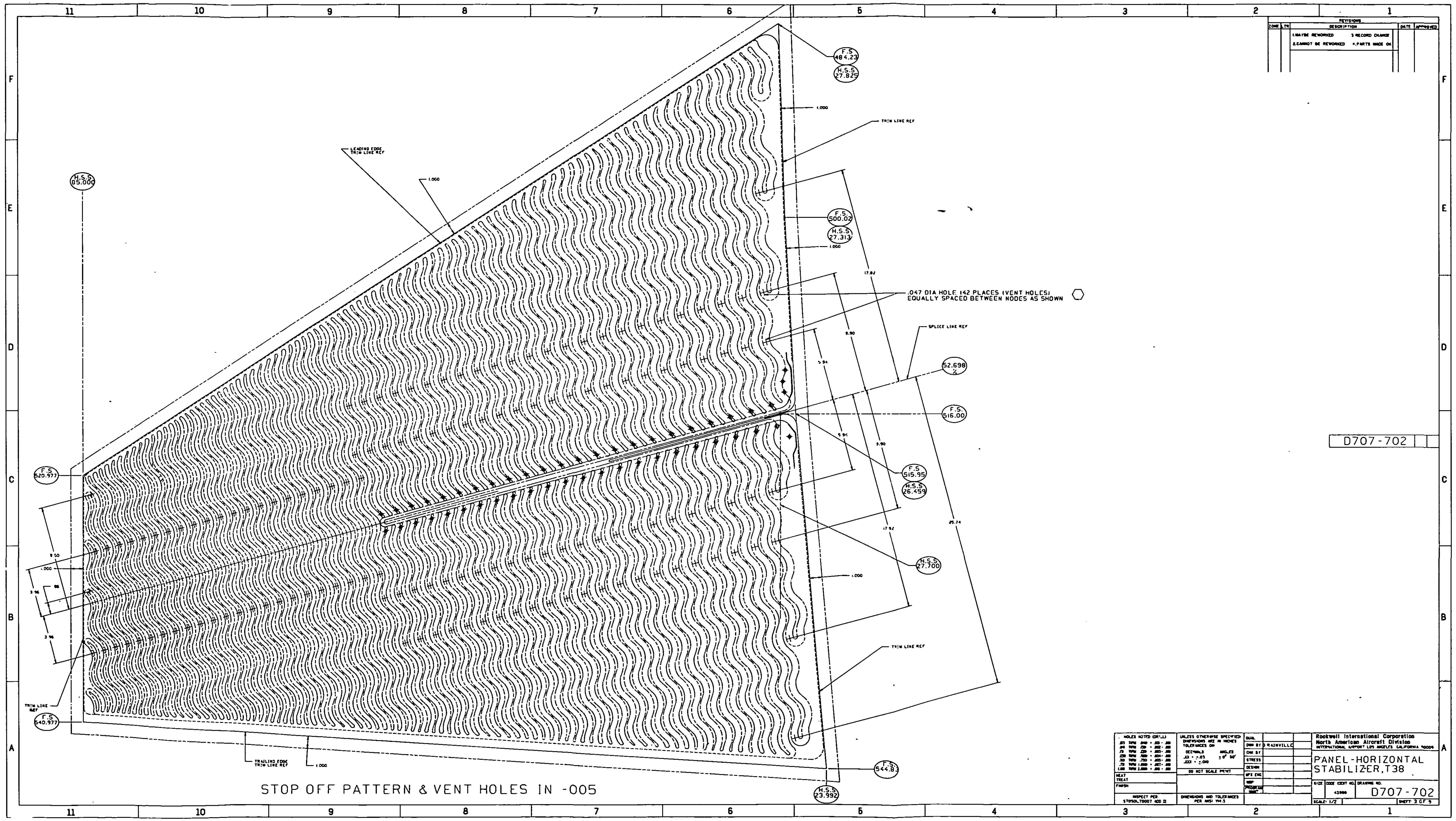


Figure 3-23. SPF/DB Horizontal Stabilizer Panel (cont)

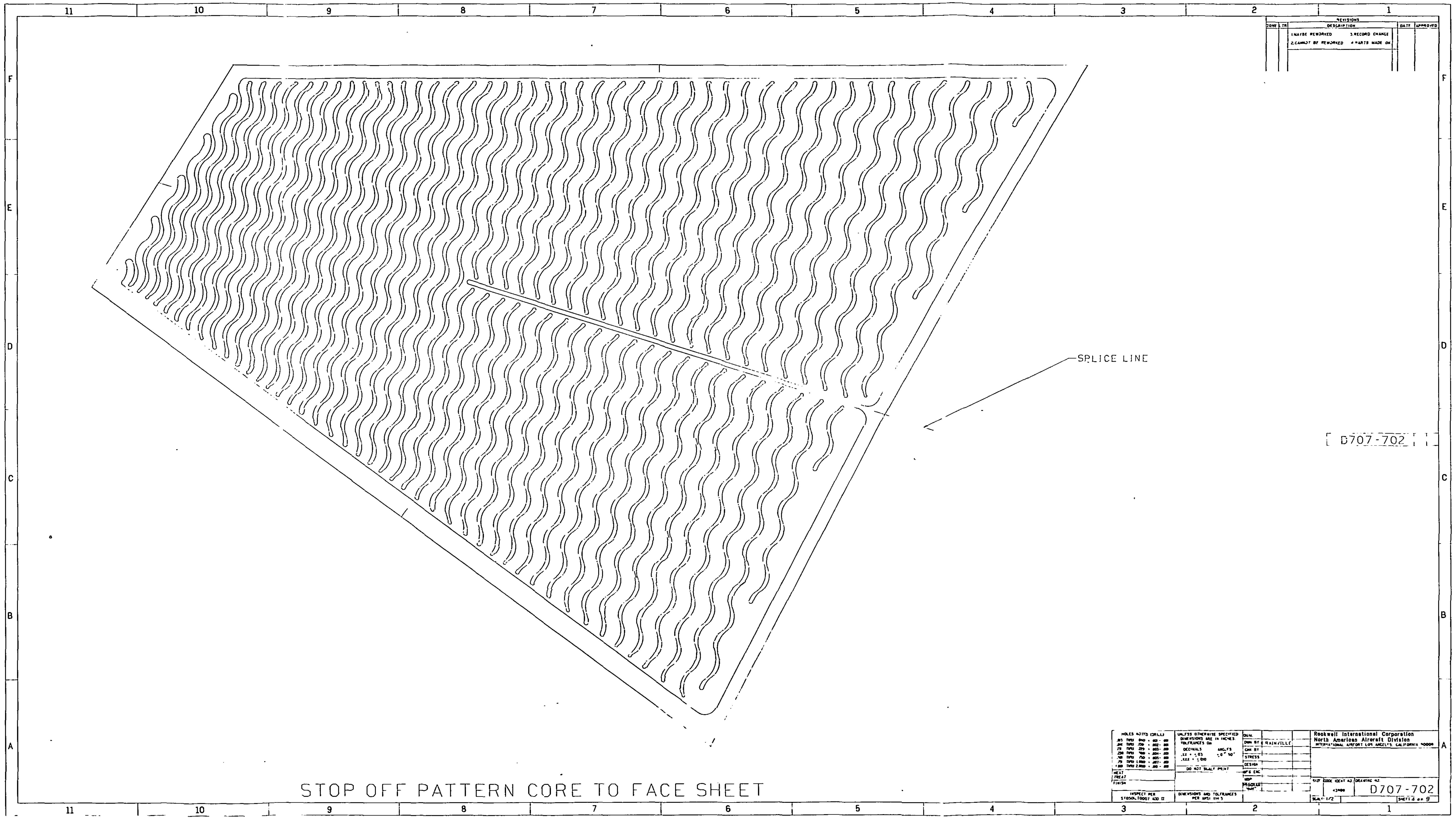


Figure 3-23. SPF/DB Horizontal Stabilizer Panel (cont)

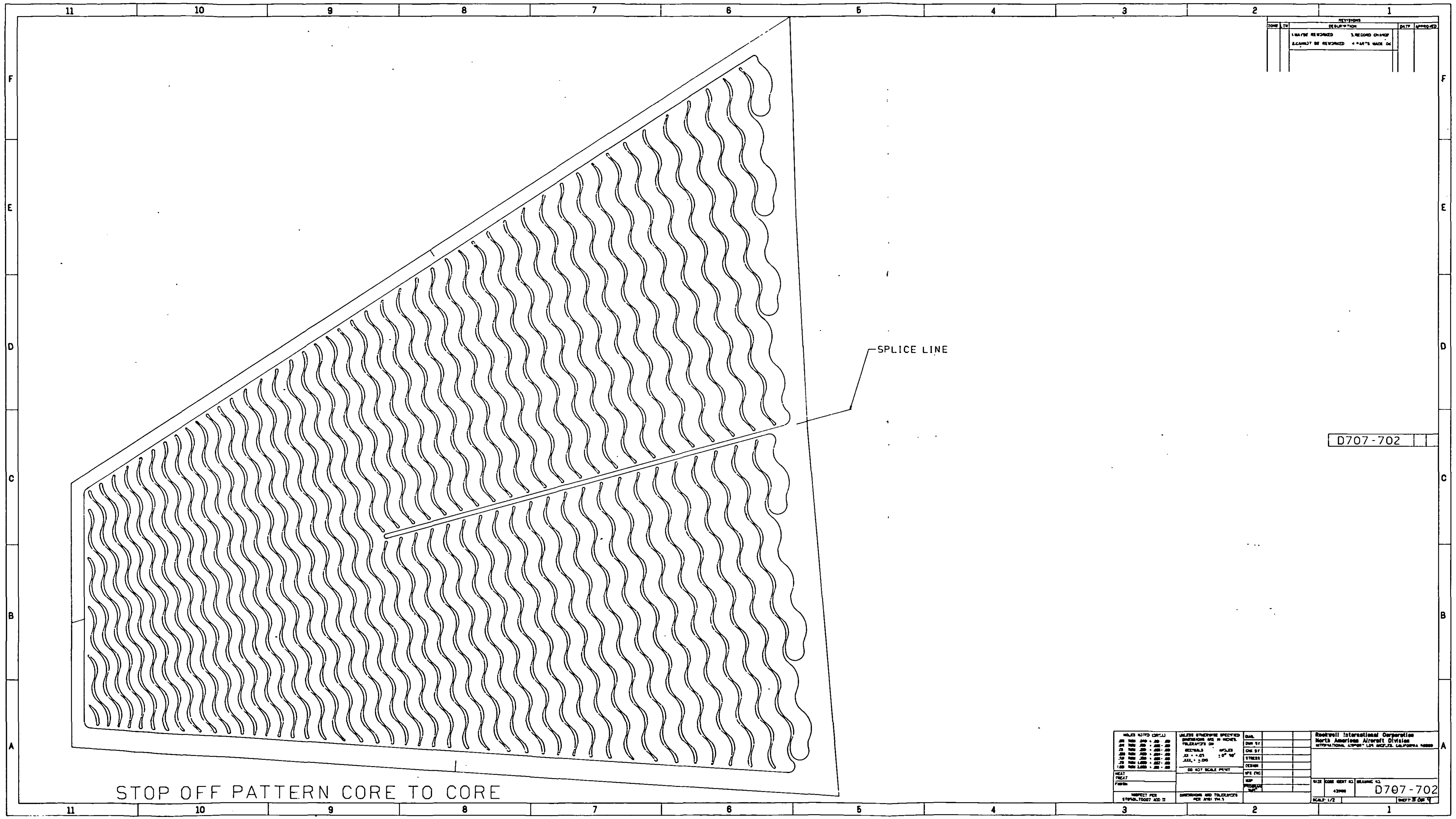


Figure 3-23. SPF/DB Horizontal Stabilizer Panel (cont)

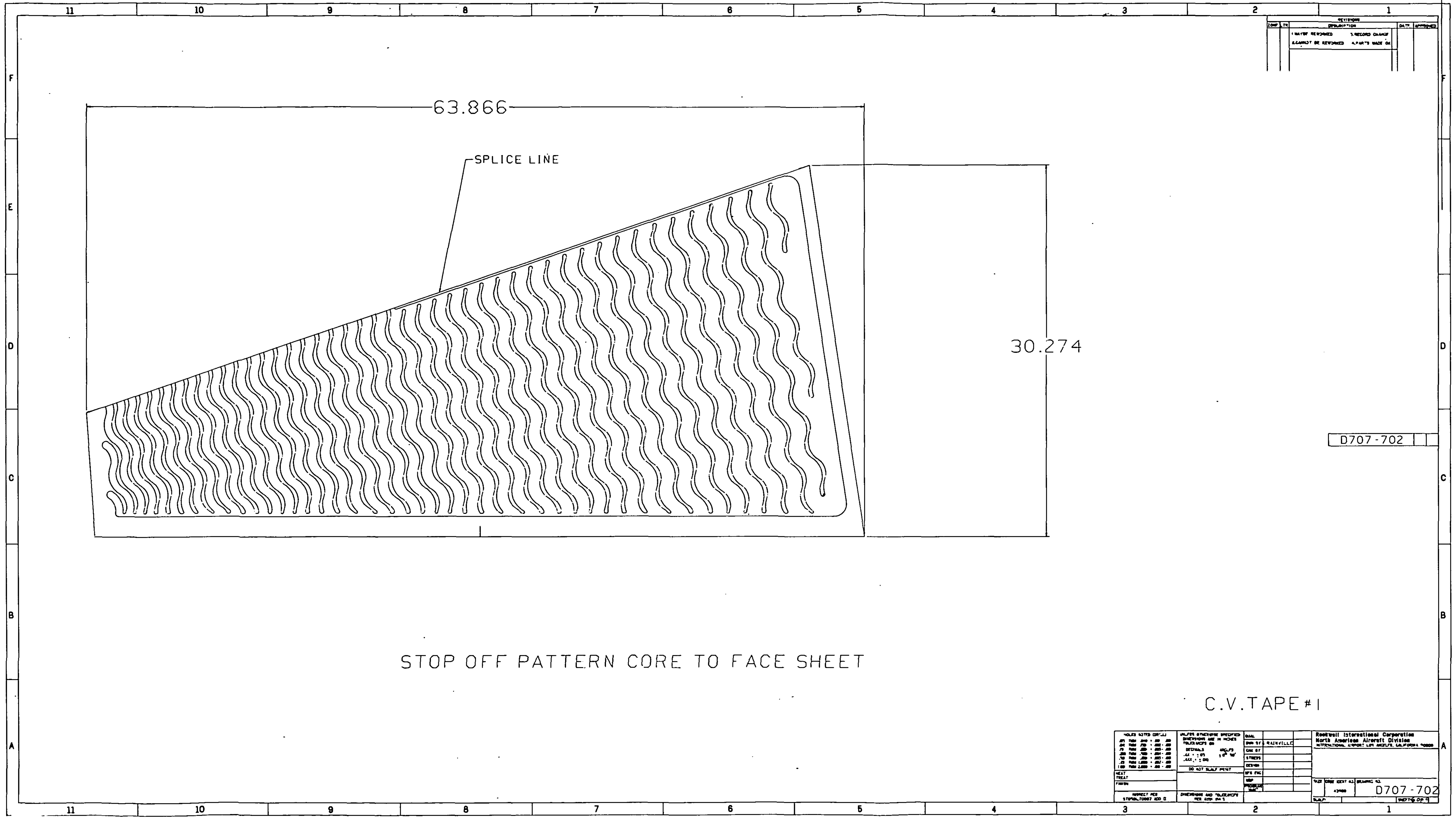


Figure 3-23 SPF/DB Horizontal Stabilizer Panel (cont)

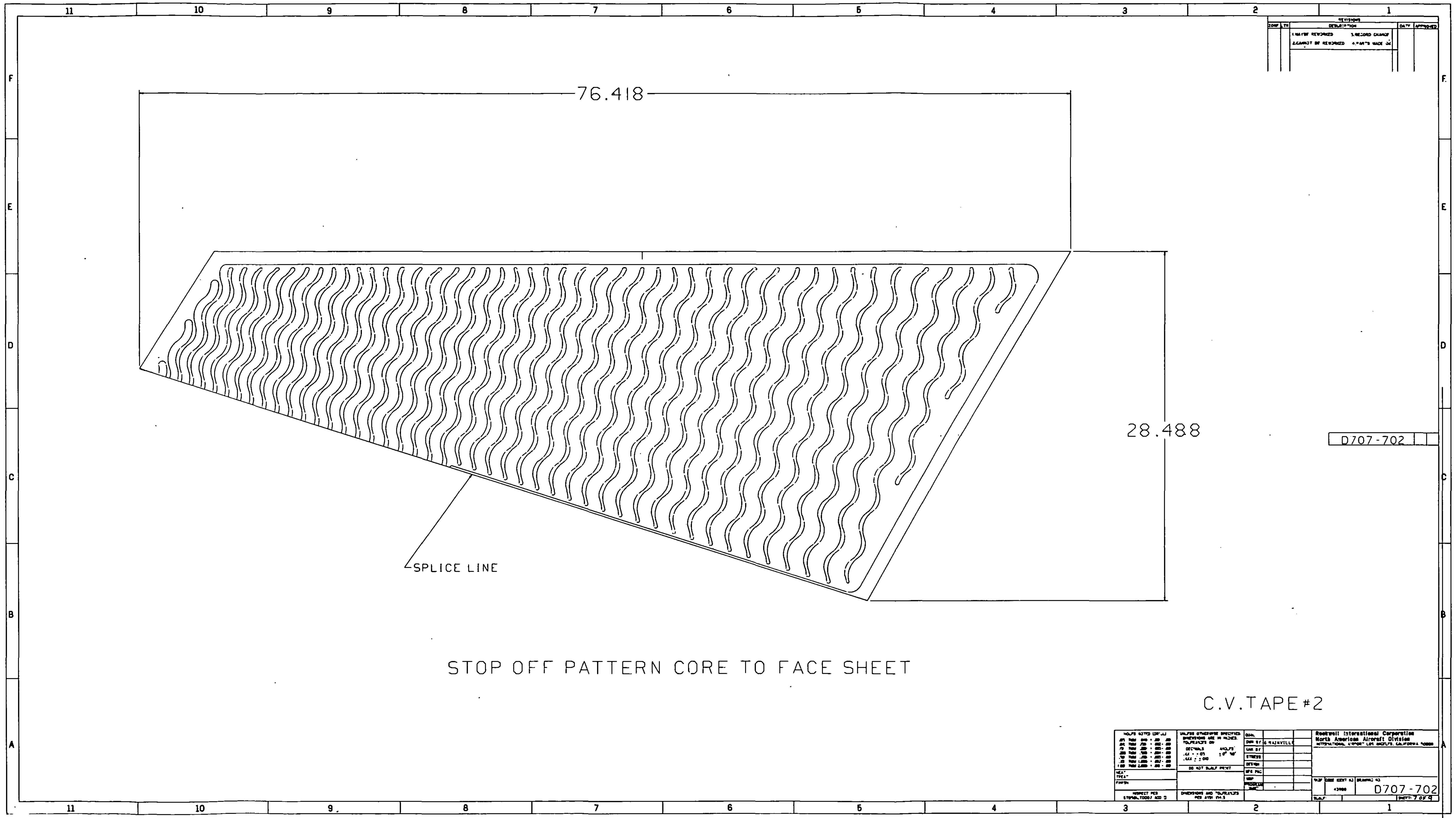


Figure 5-23 SPF/DB Horizontal Stabilizer Panel (cont)

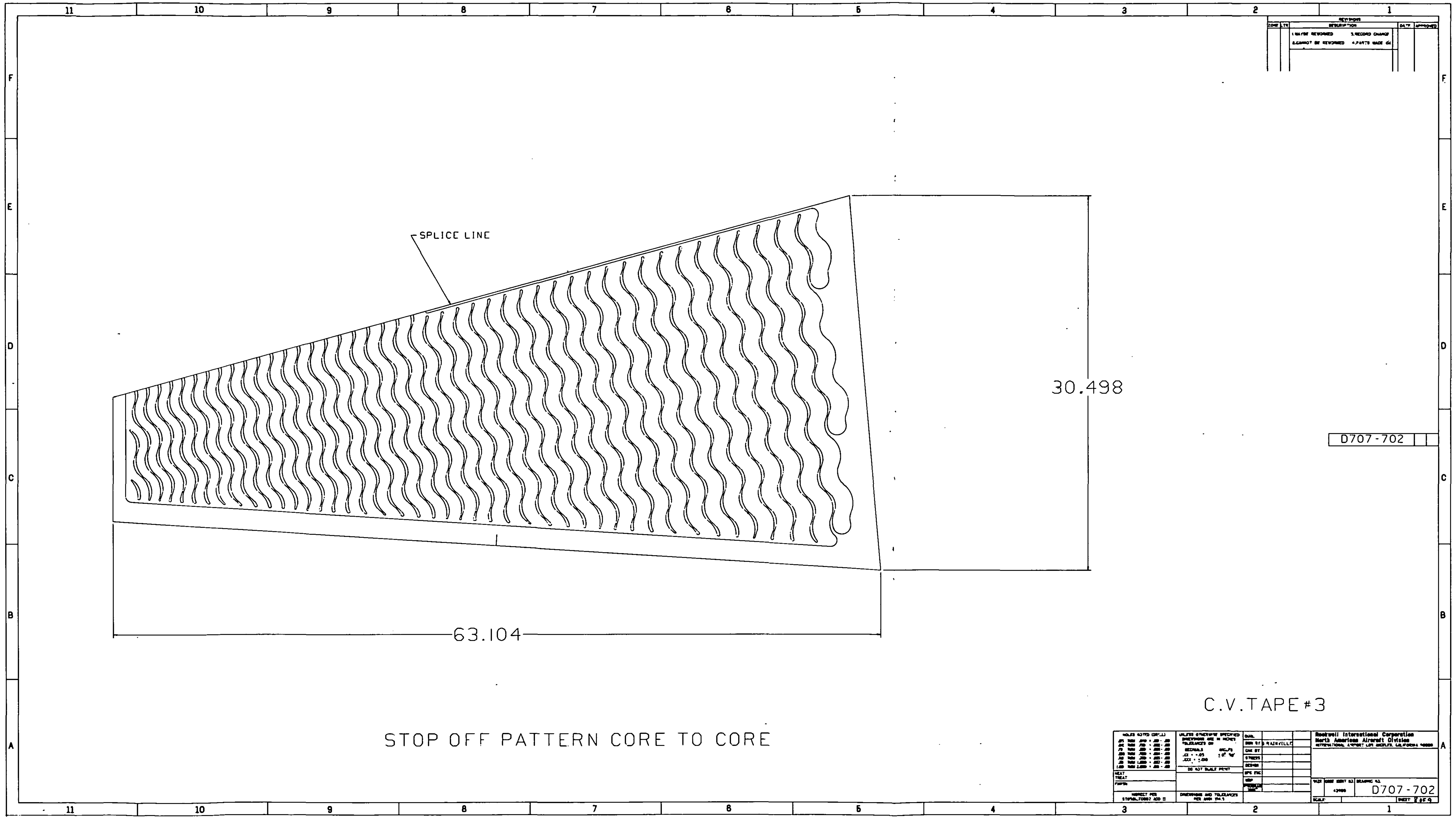


Figure 3-23 SFP/DV Horizontal Stabilizer Panel (cont)

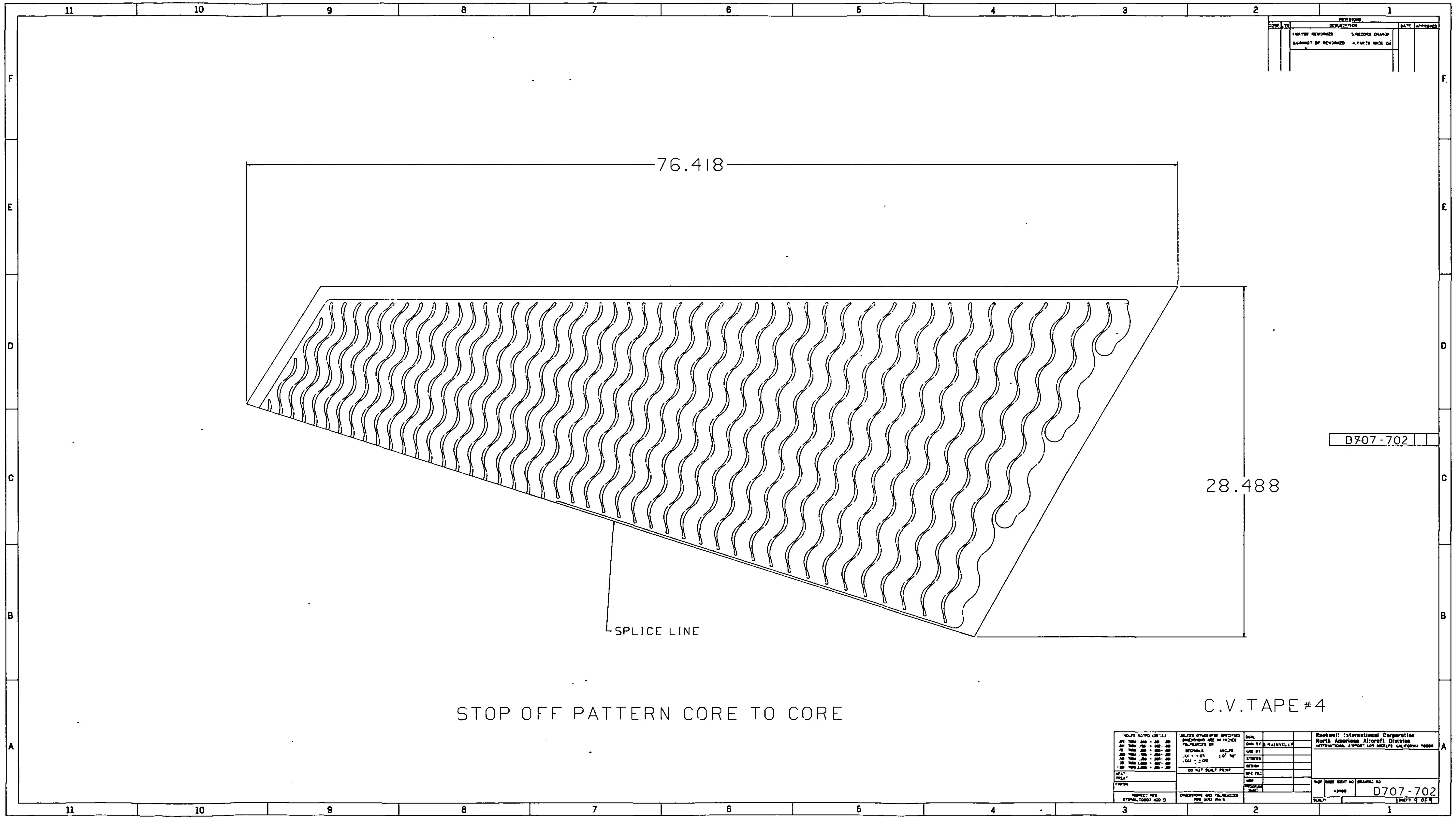


Figure 3-23 SPF/DB Horizontal Stabilizer Panel (concl)

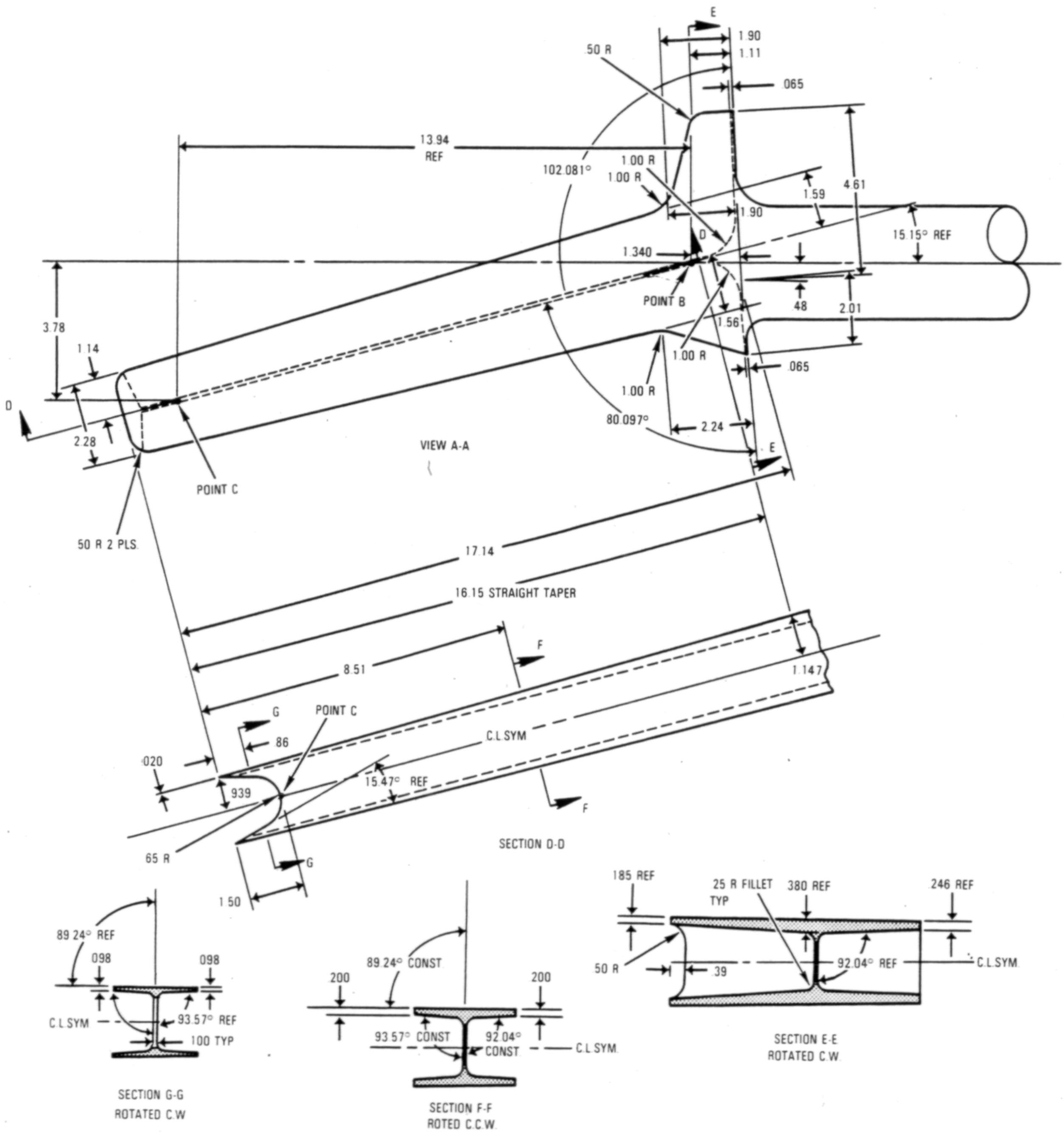


Figure 3-24. Spindle Detail

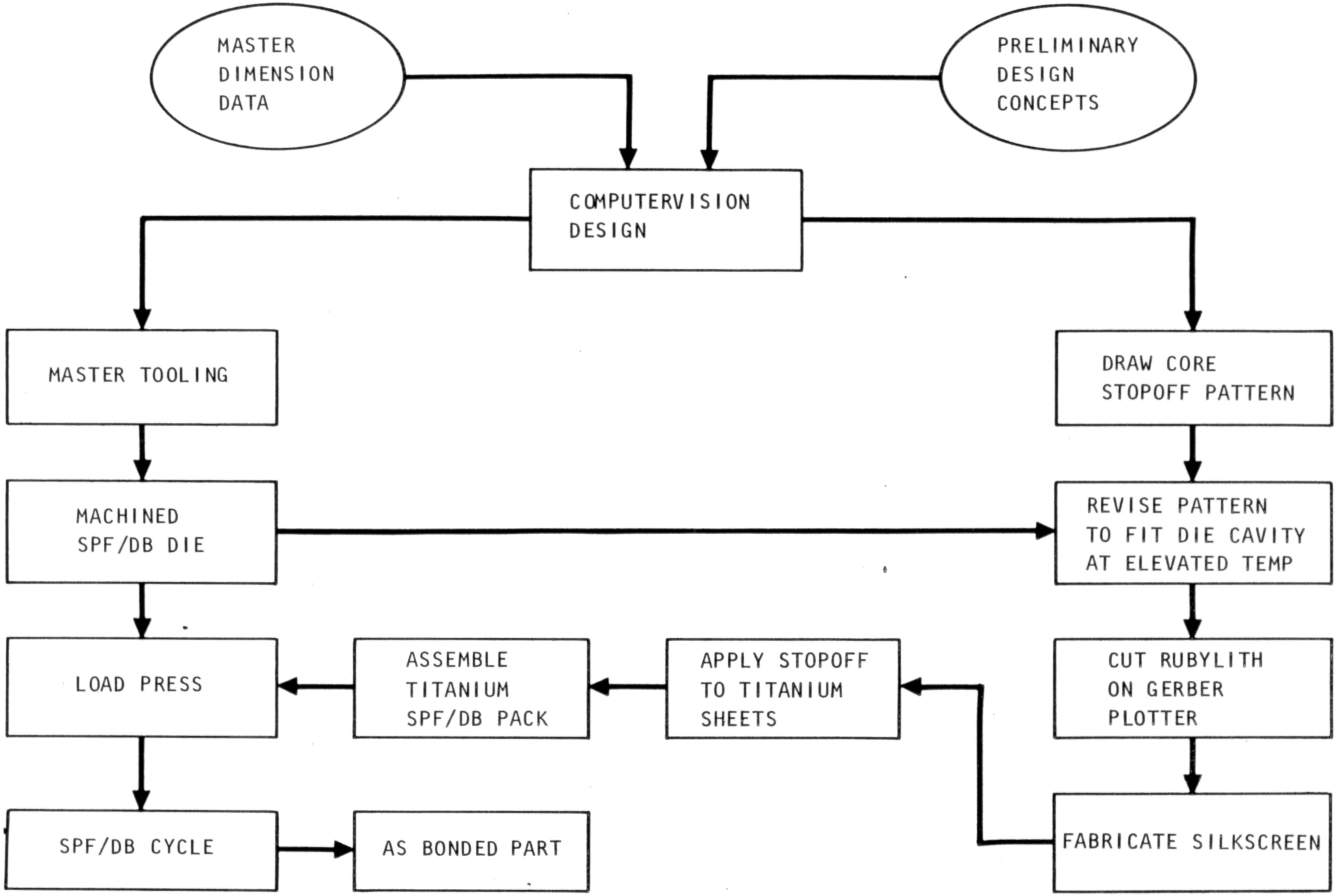


Figure 3-25. Computer-Aided Design and Fabrication Process

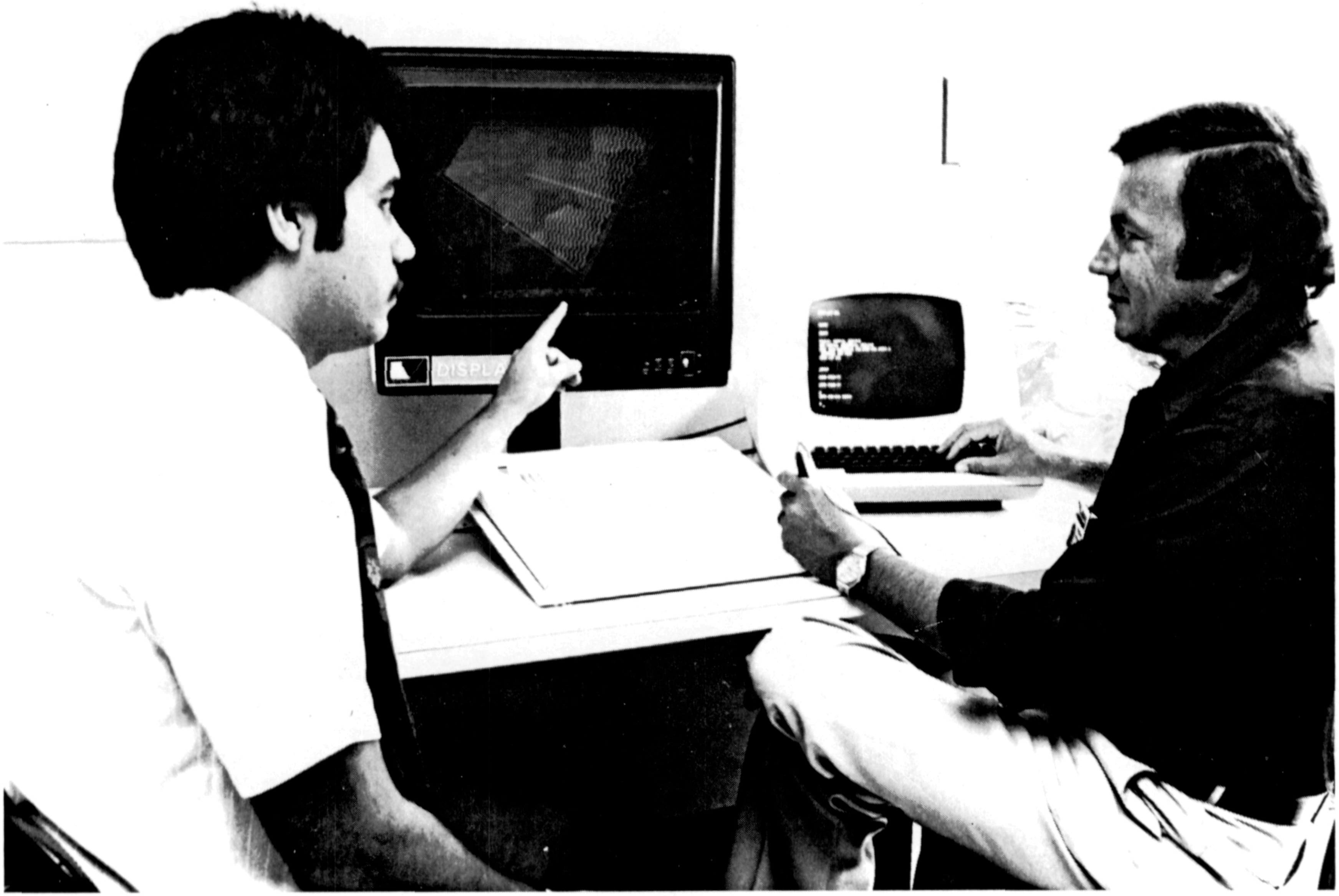


Figure 3-26. Interactive Graphics Terminal

Figure 3-27. Stopoff Pattern on Gerber Plotter

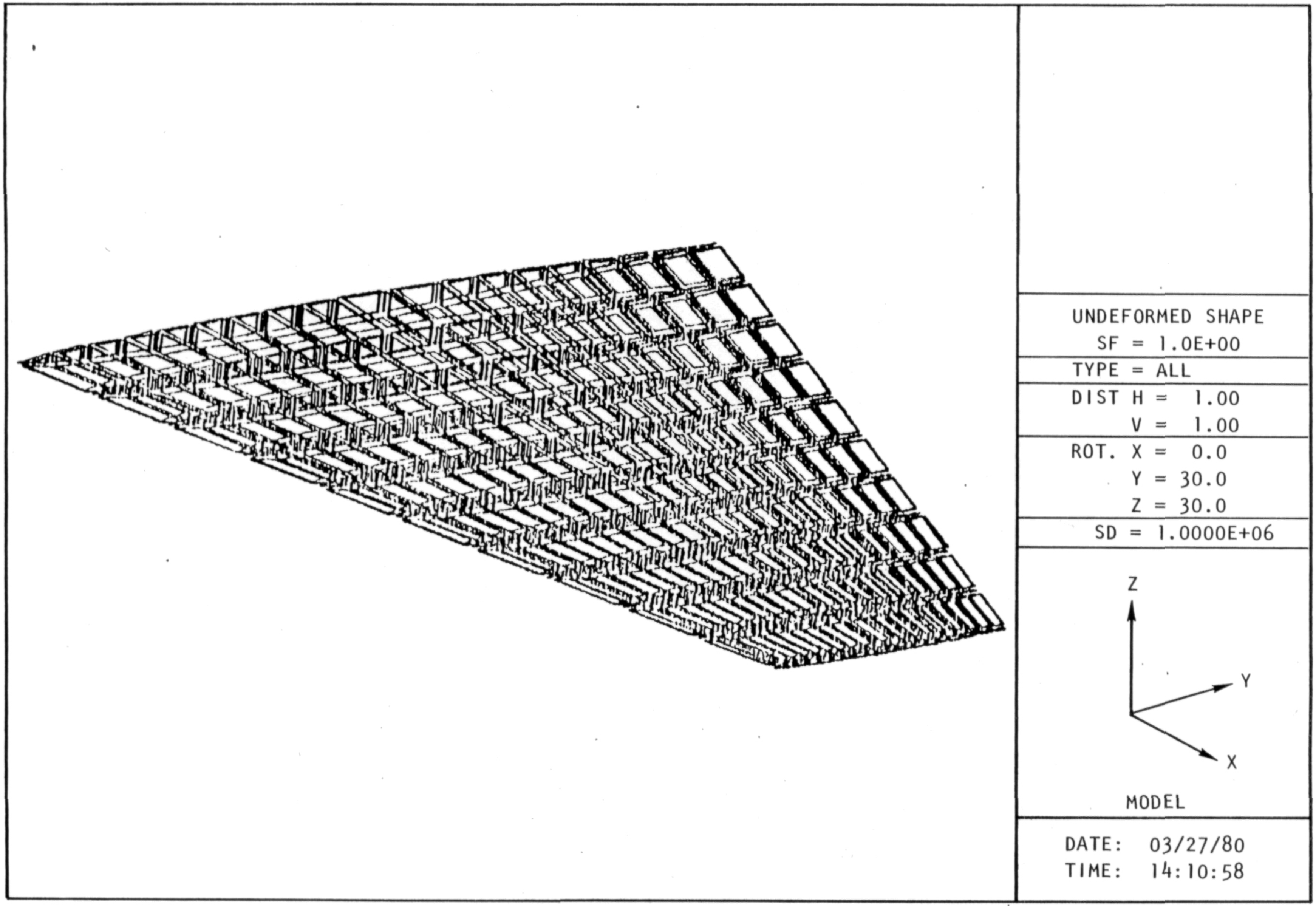


Figure 3-28. T-38 Horizontal Stabilizer NASTRAN Finite-Element Model

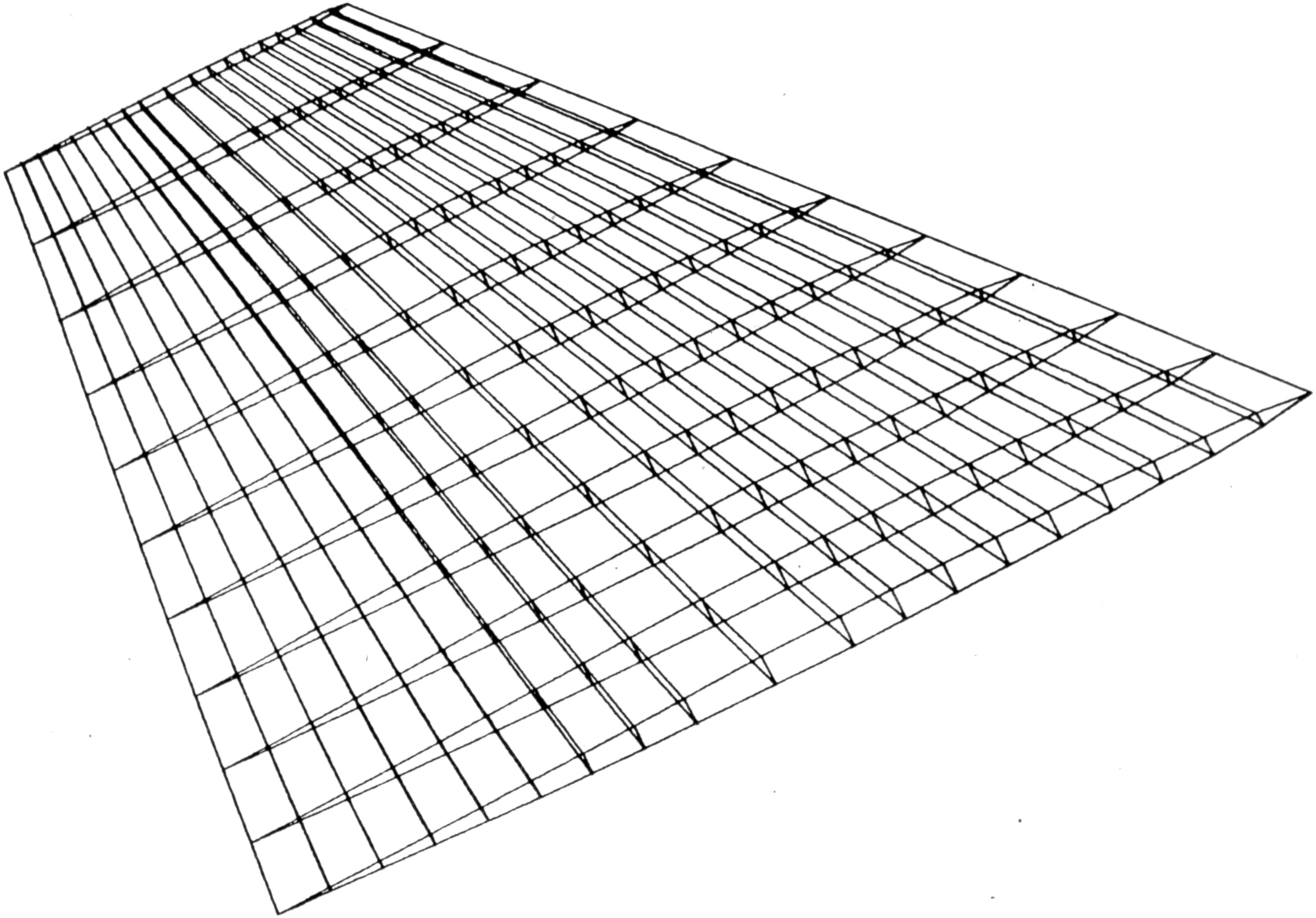


Figure 3-29. T-38 Horizontal Stabilizer NASTRAN Model

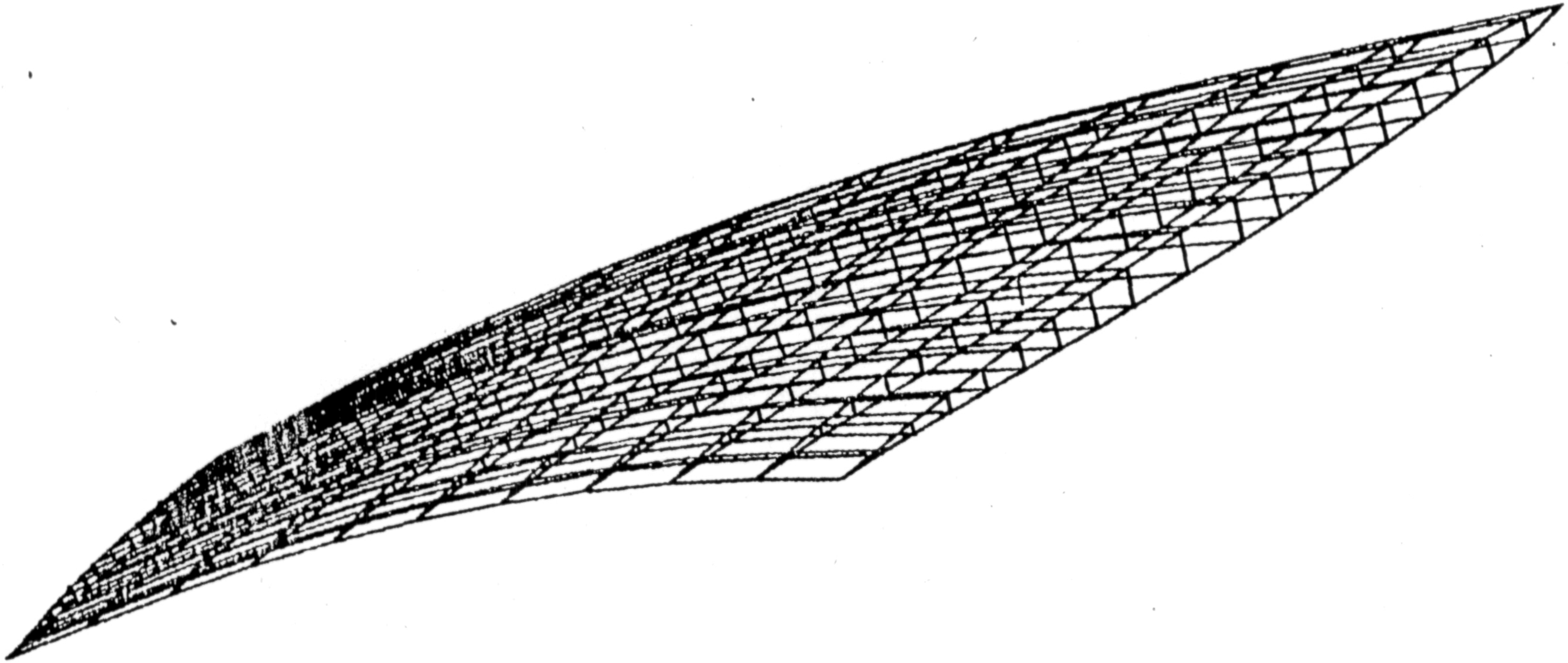


Figure 3-30. T-38 Horizontal Stabilizer NASTRAN Finite-Element Model

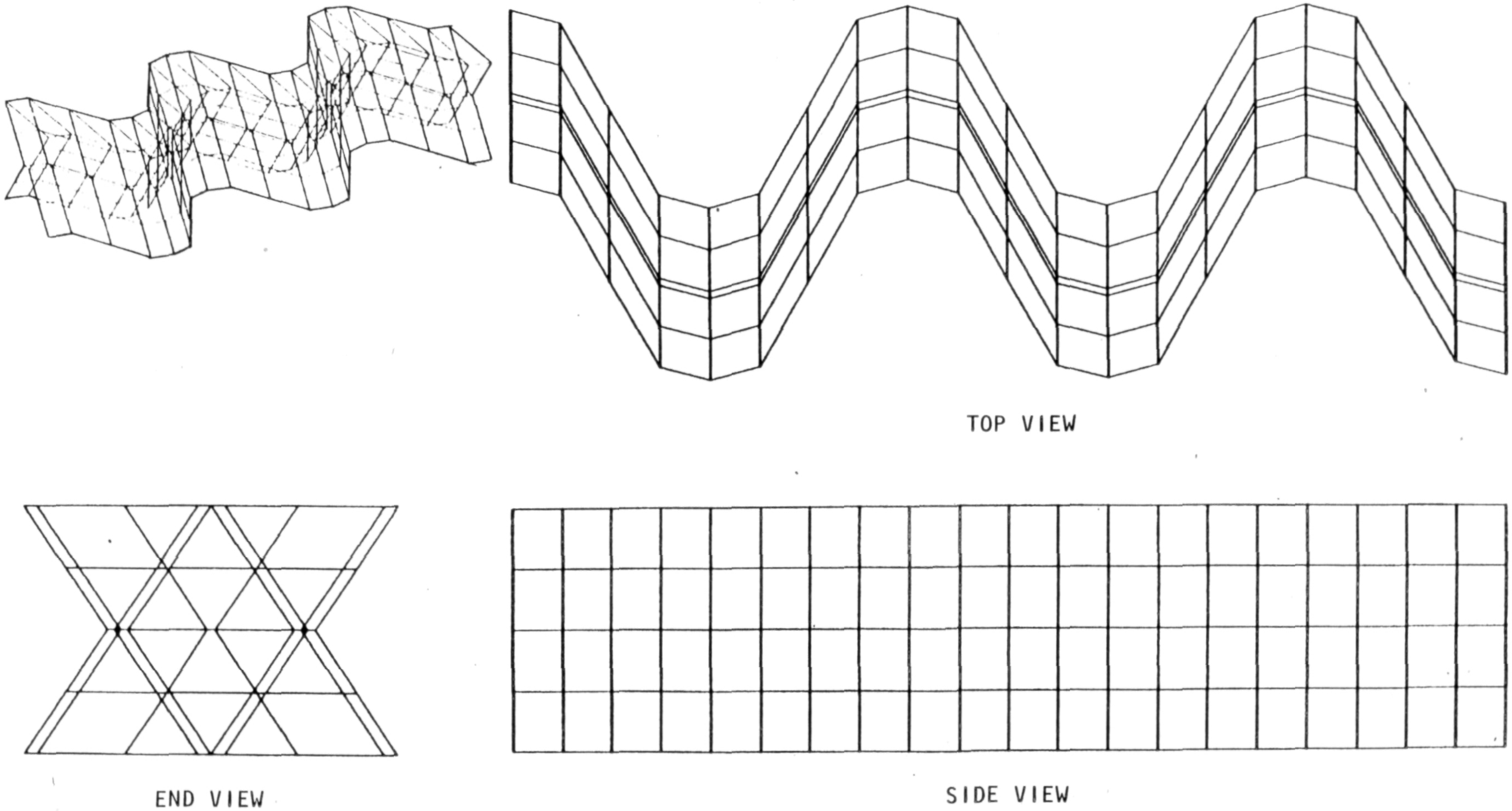


Figure 3-31. Four-Sheet Technology NASTRAN Model

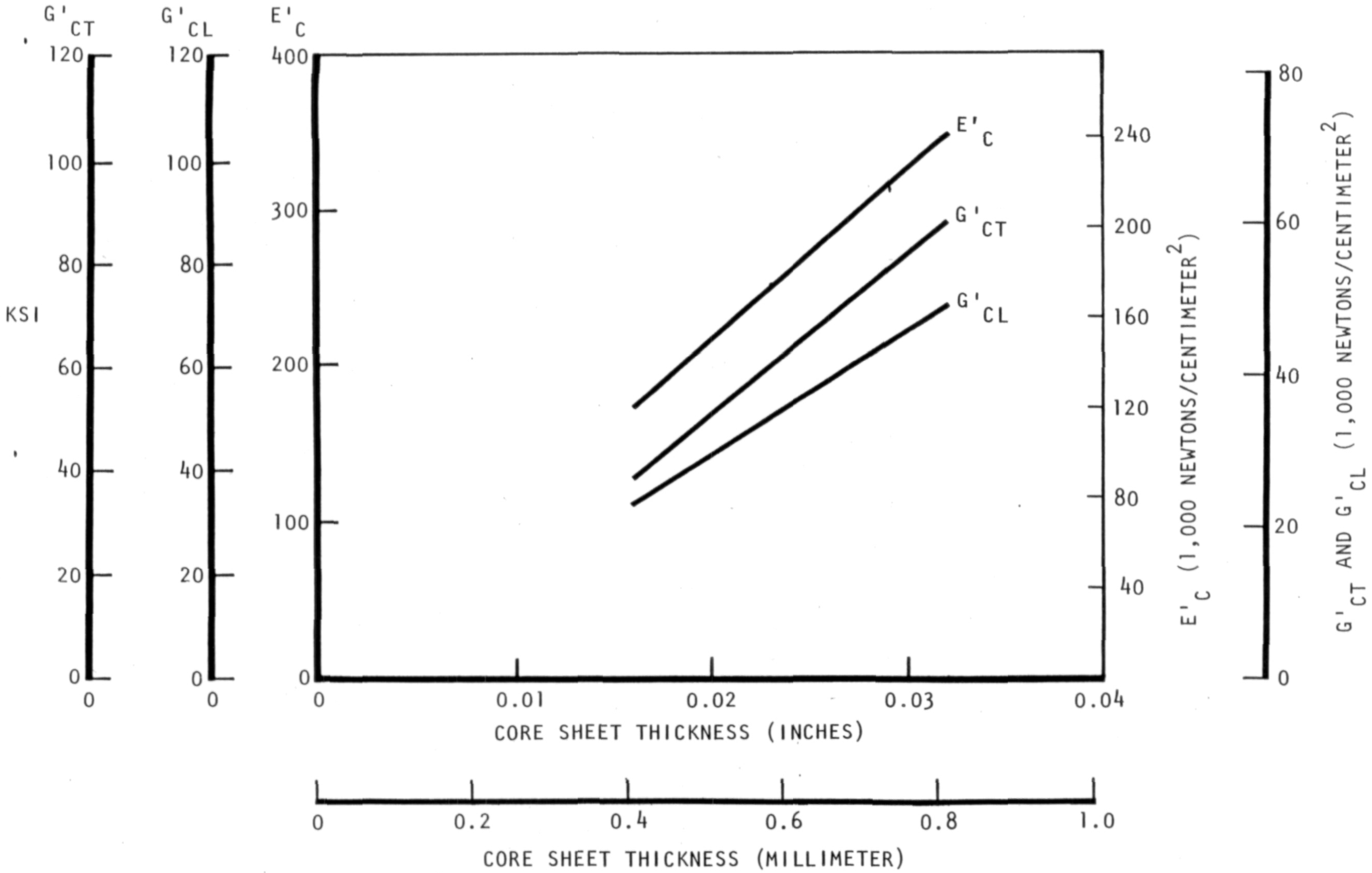


Figure 3-32. Four-Sheet Sandwich Core Sheet Variation

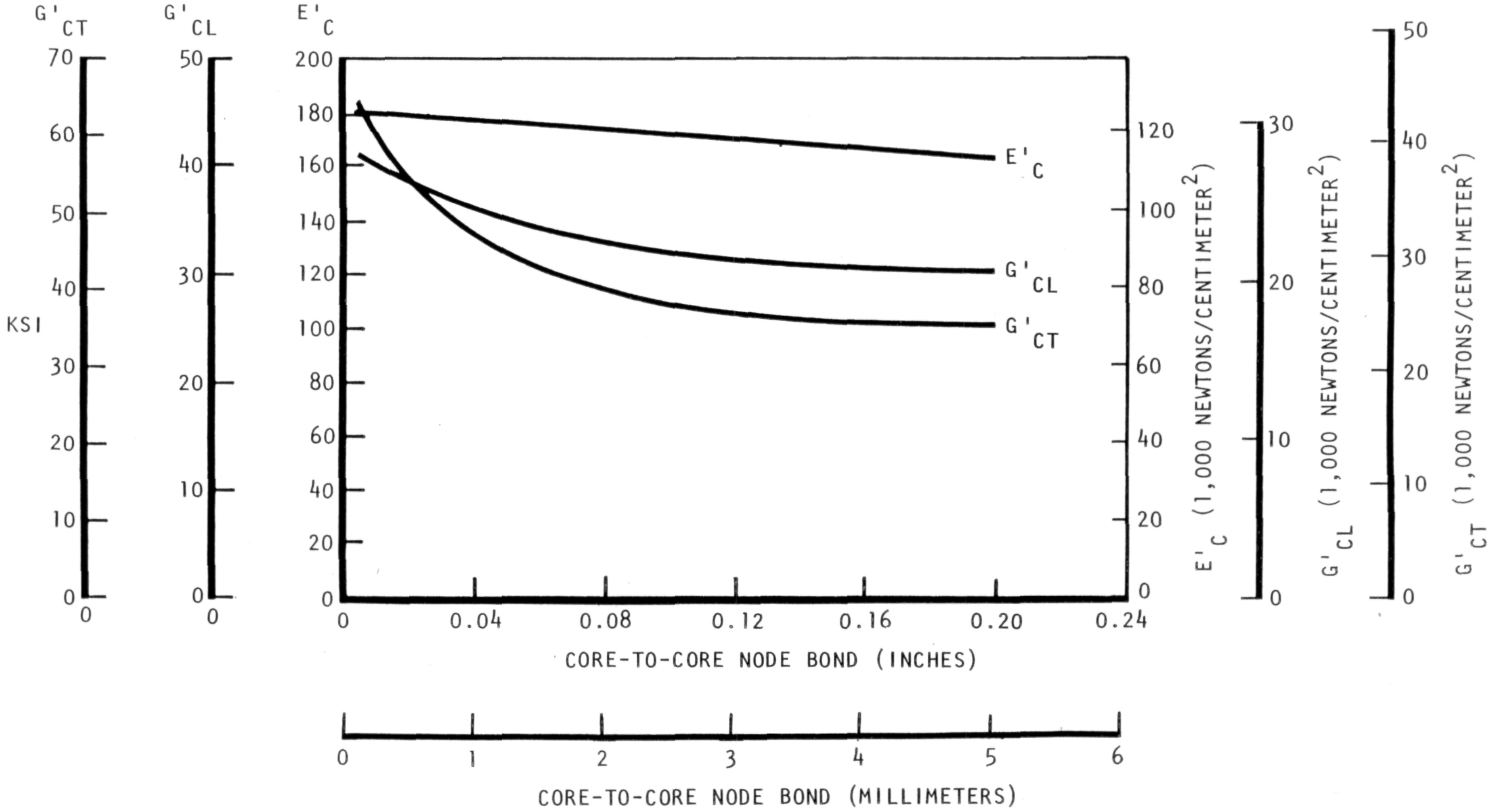


Figure 3-33. Four-Sheet Sandwich Node Width Variation

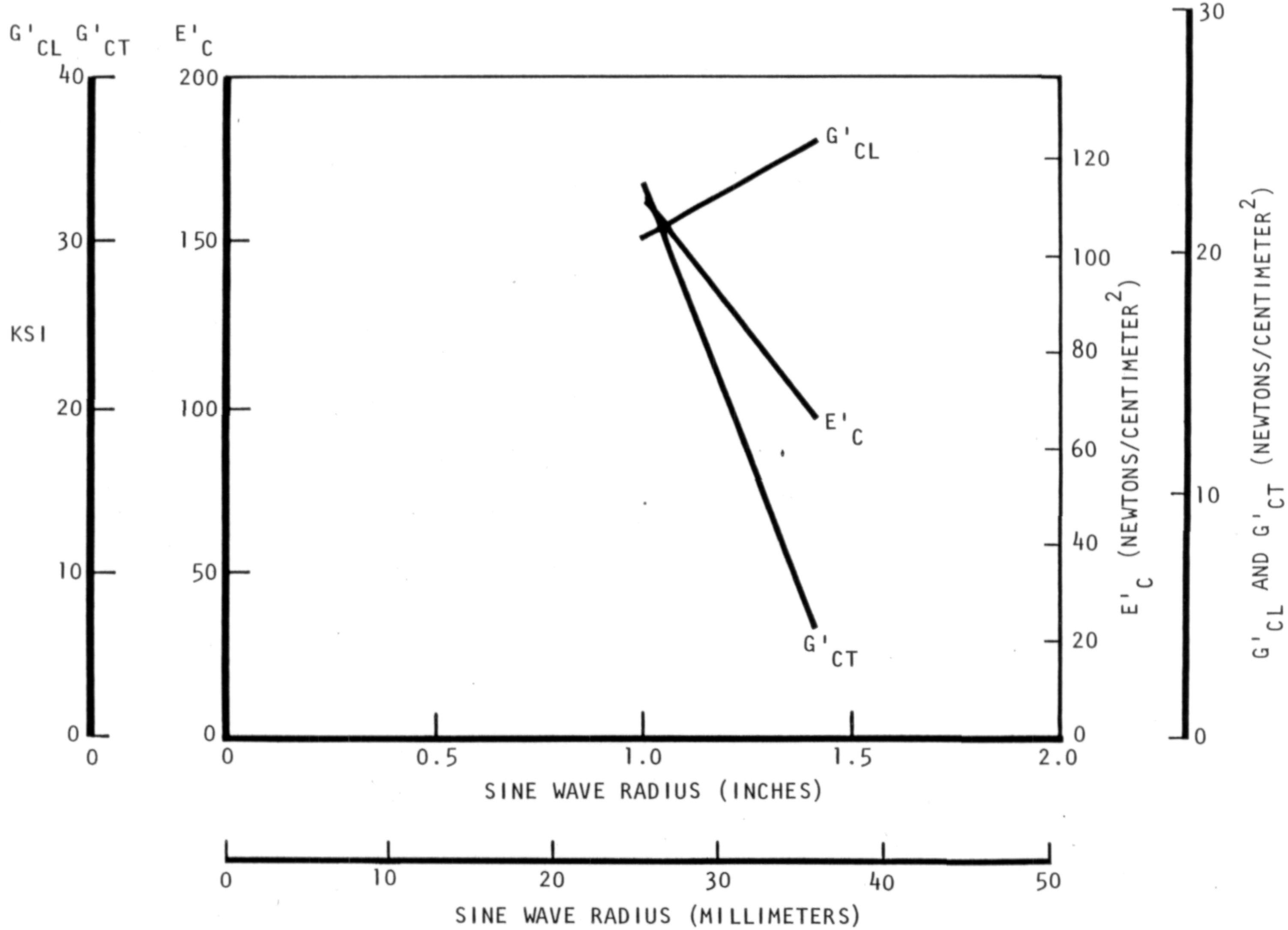


Figure 3-34. Four-Sheet Sandwich Sine Wave Radius Variation

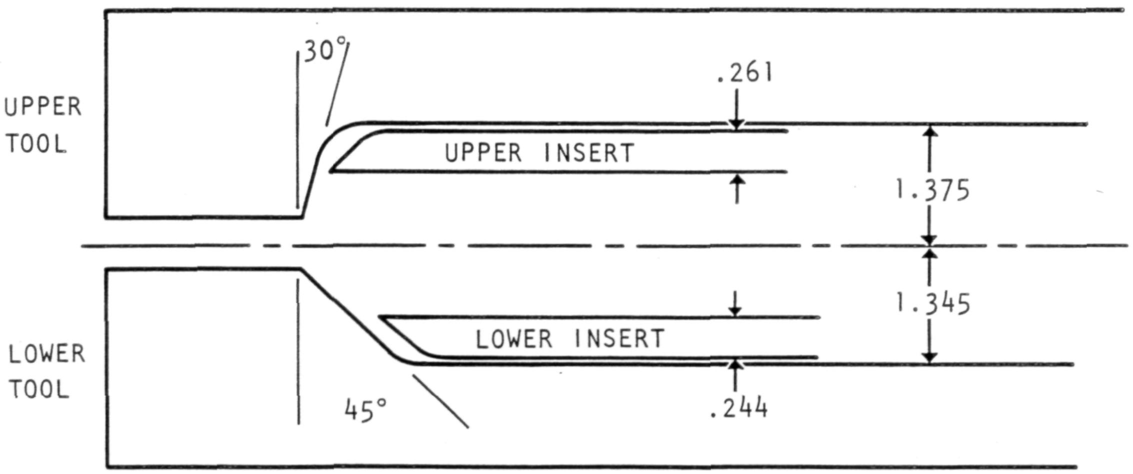


Figure 3-35. Tool Cavity

Figure 3-36. T-38 Horizontal Stabilizer Panel Tool Drawing

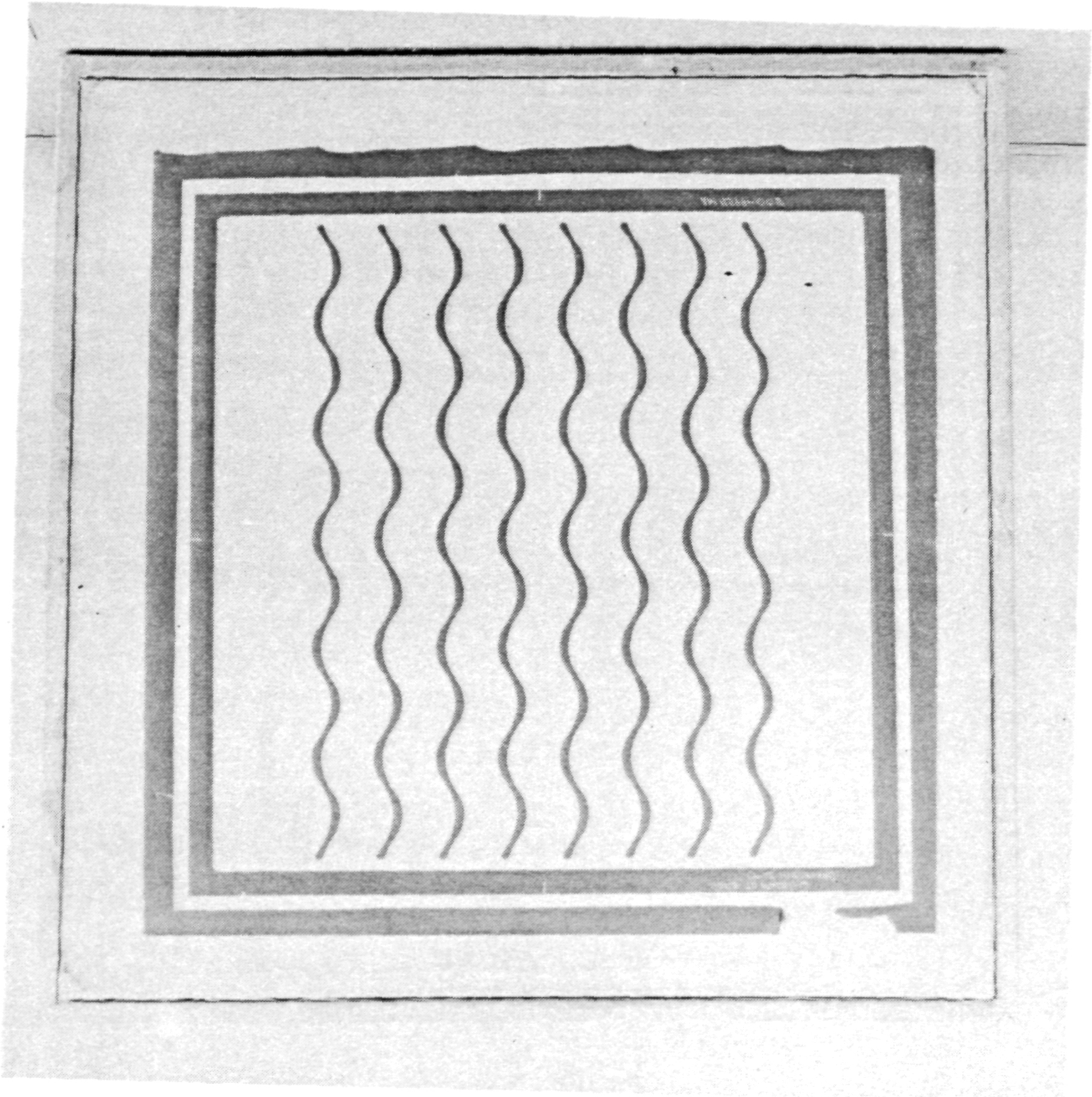


Figure 3-37. Silk Screen with Sinewave Pattern

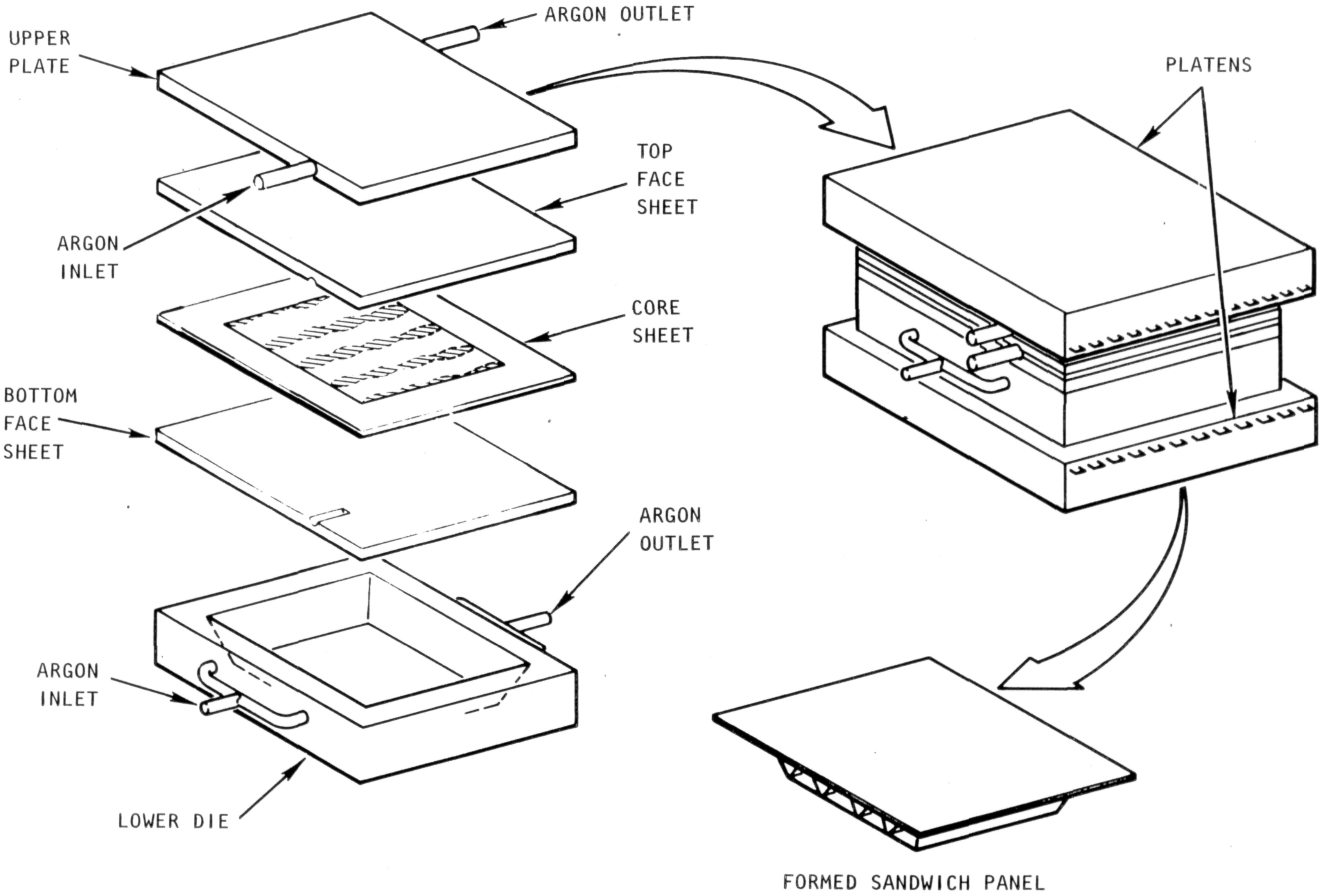


Figure 3-38. SPF/DB Pack Assembly

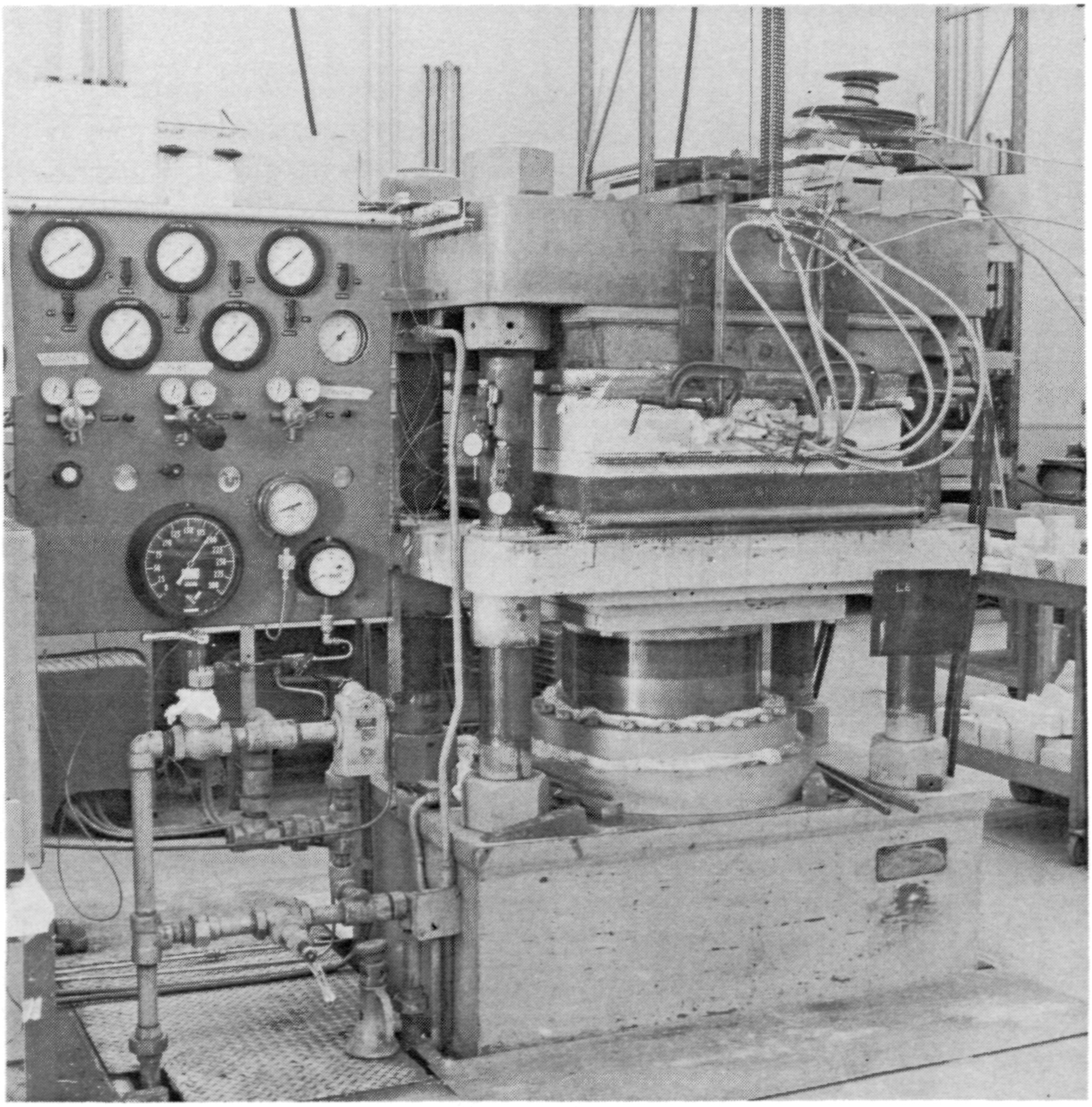


Figure 3-39. 300-Ton Hydraulic Press

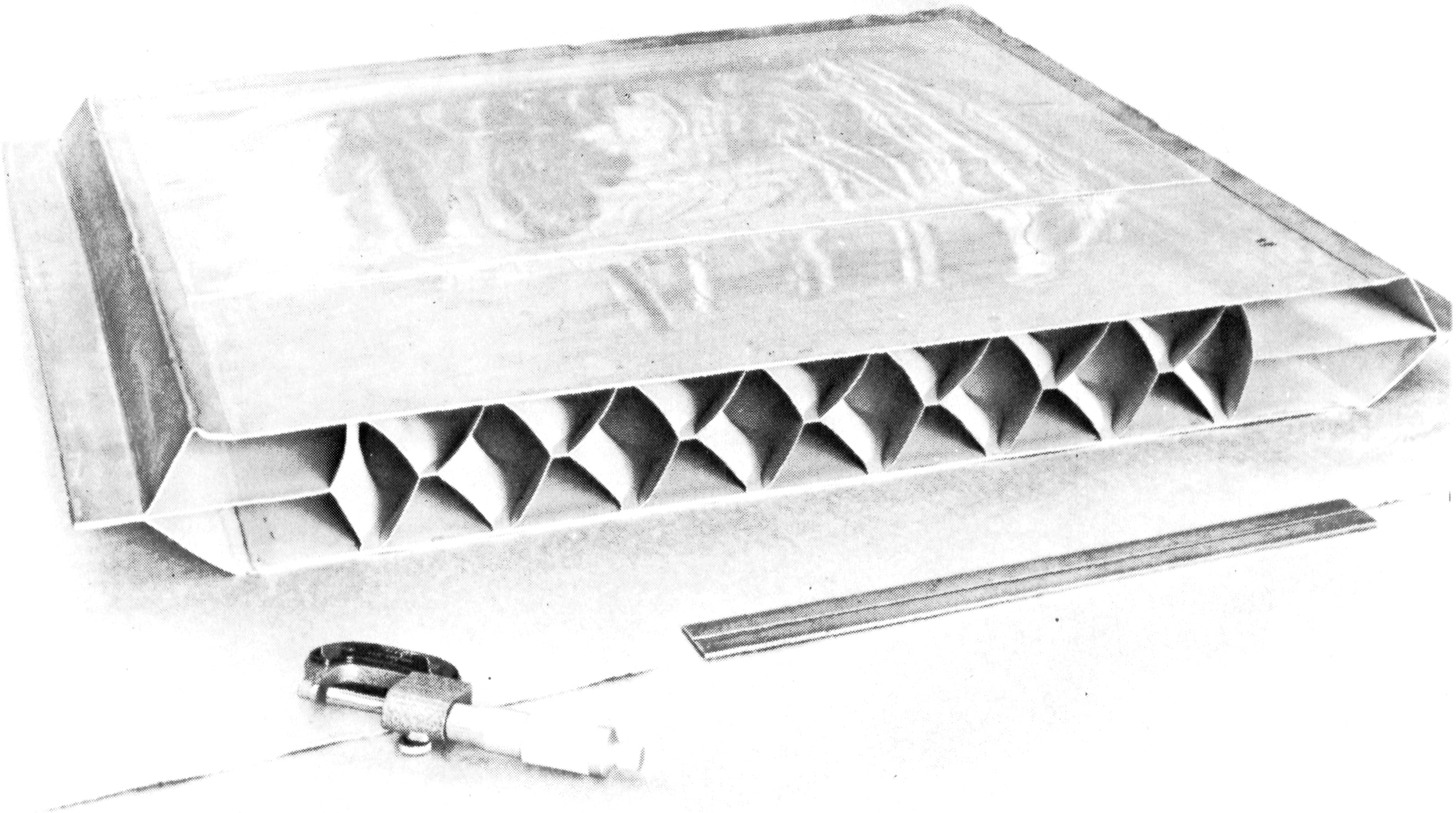


Figure 3-40. Four-Sheet Technology Panel

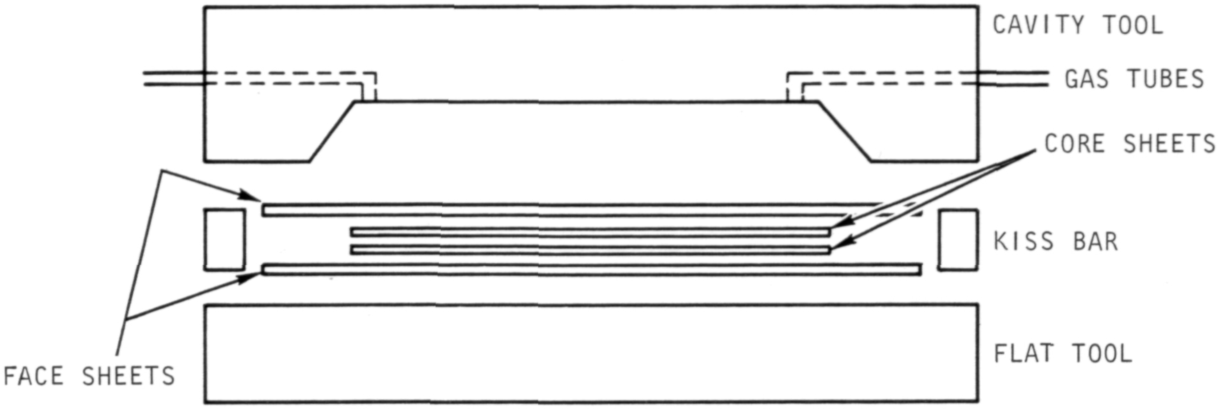


Figure 3-41. Tooling Setup for Flat Gas Bonding 7

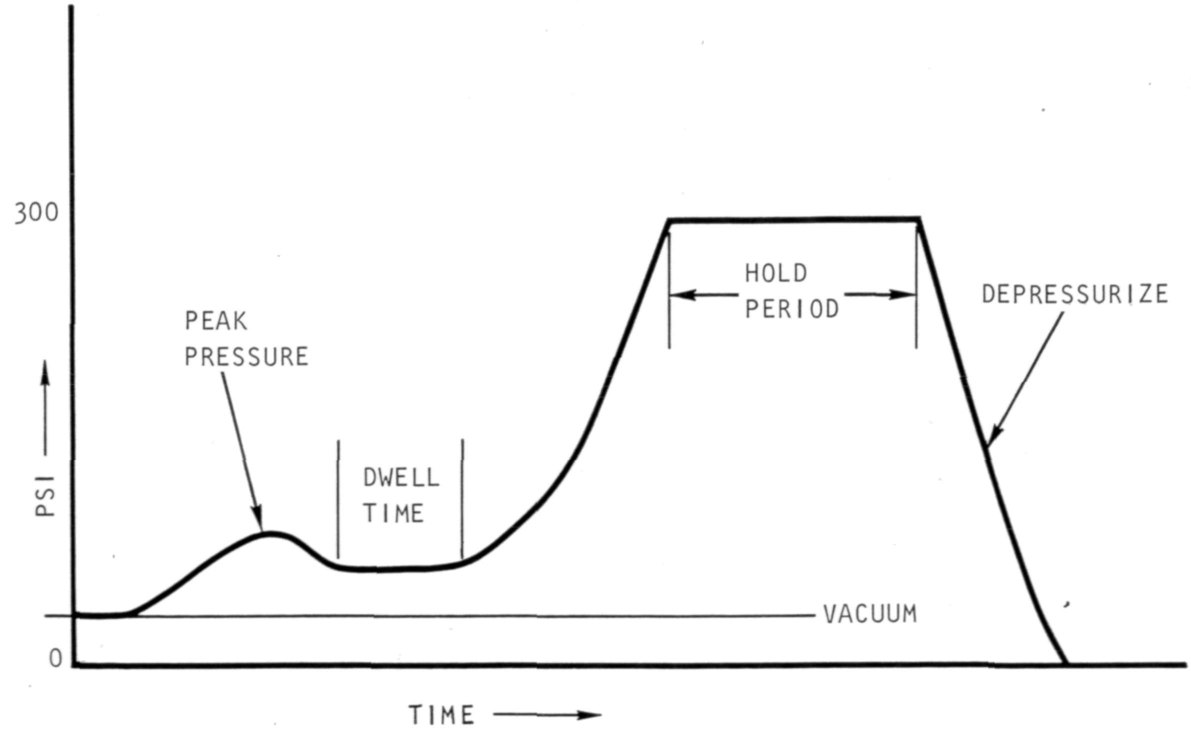


Figure 3-42. Typical Pressure/Temperature Cycle

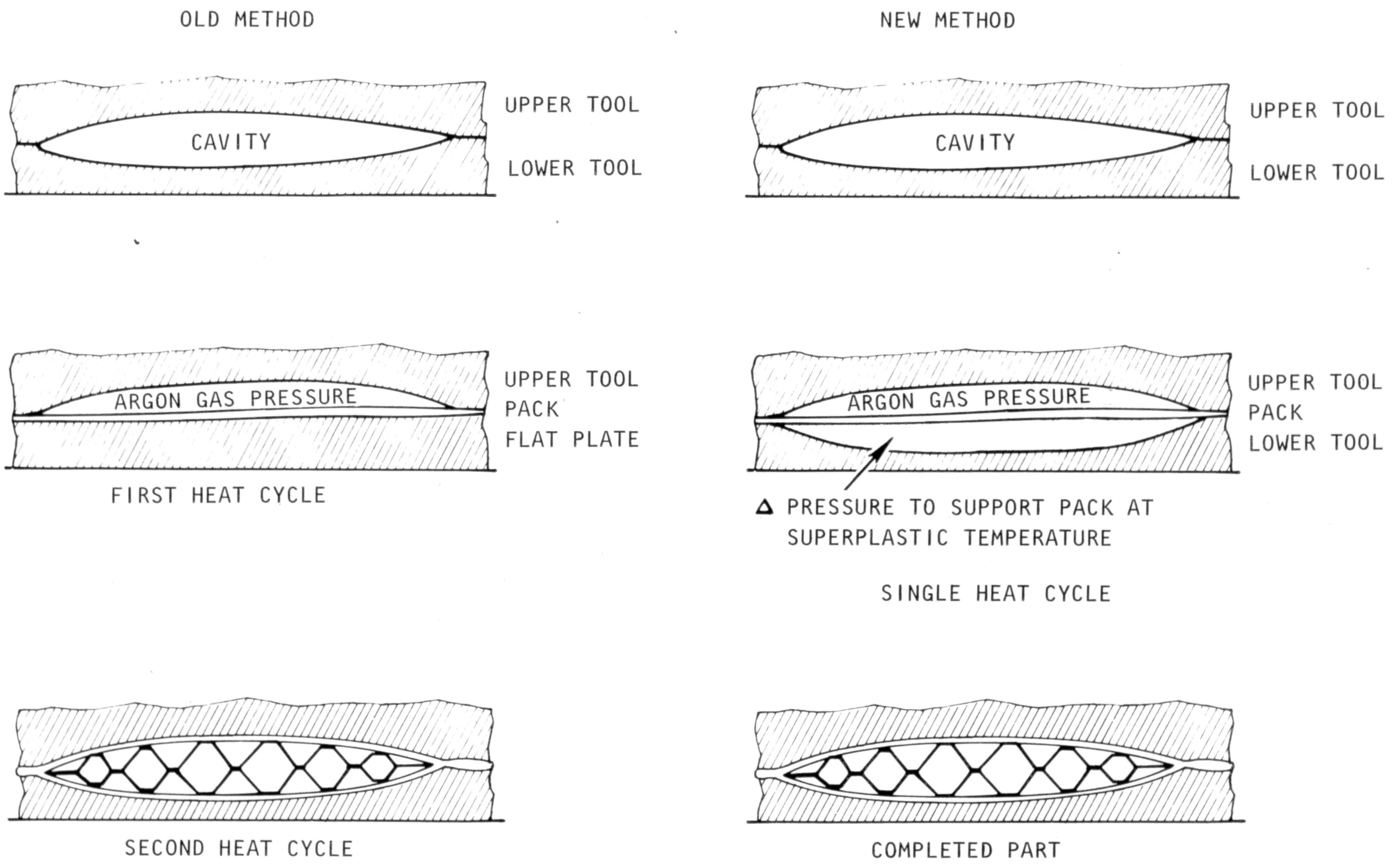


Figure 3-43. Alternate One and Two Heat Cycle Fabrication Methods

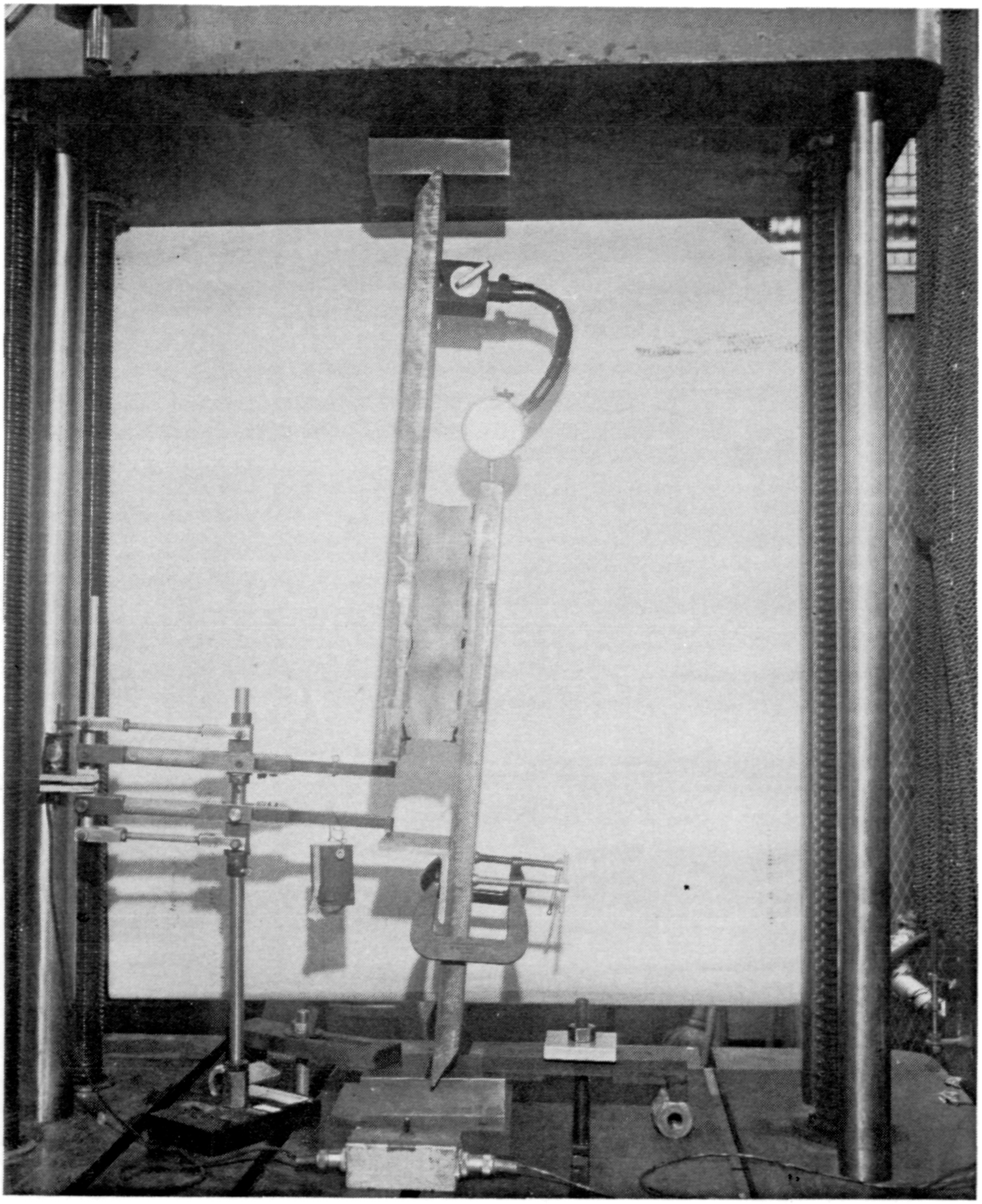


Figure 3-44. Test Setup - Core Shear Specimen

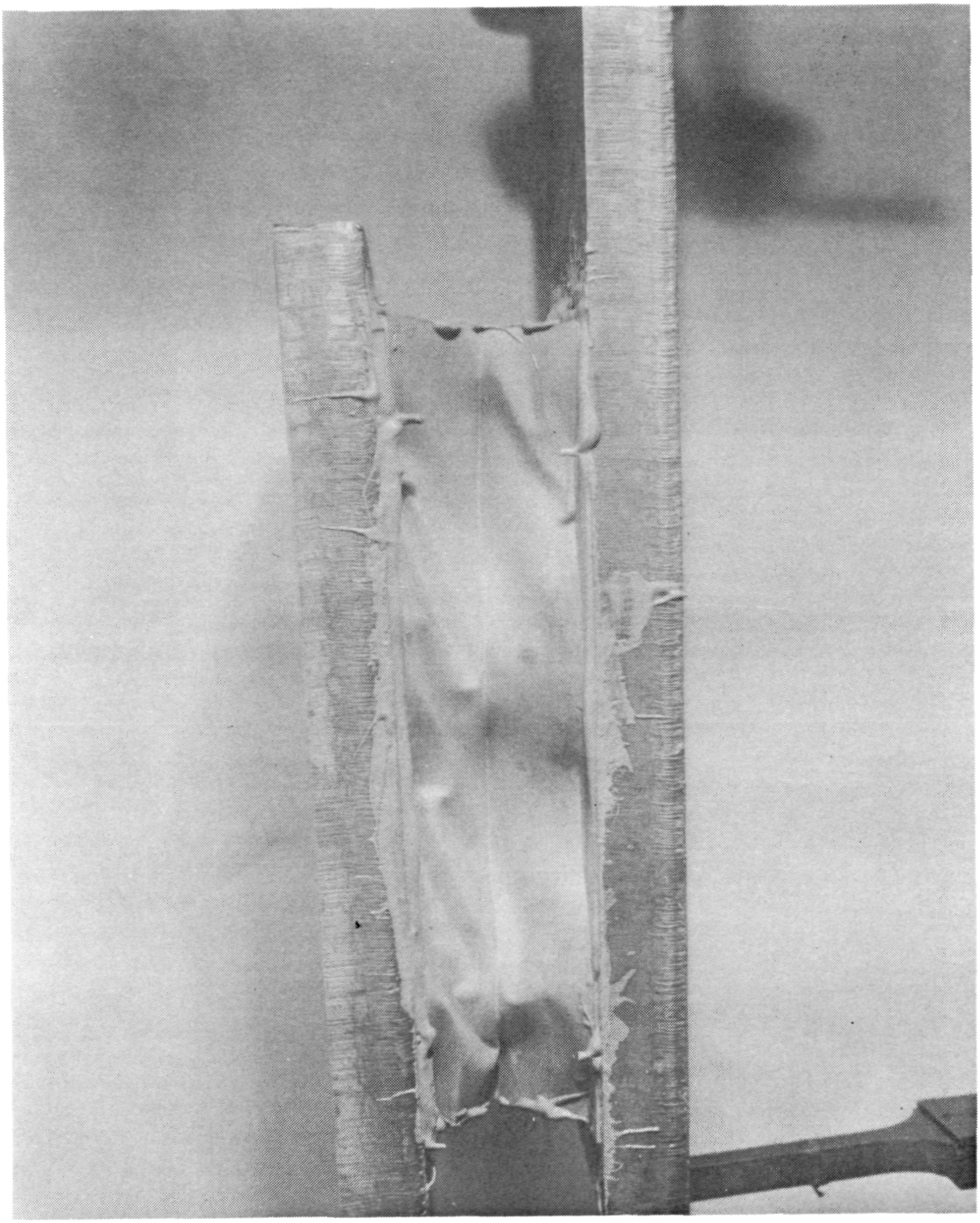


Figure 3-45. Longitudinal Core Shear Specimen

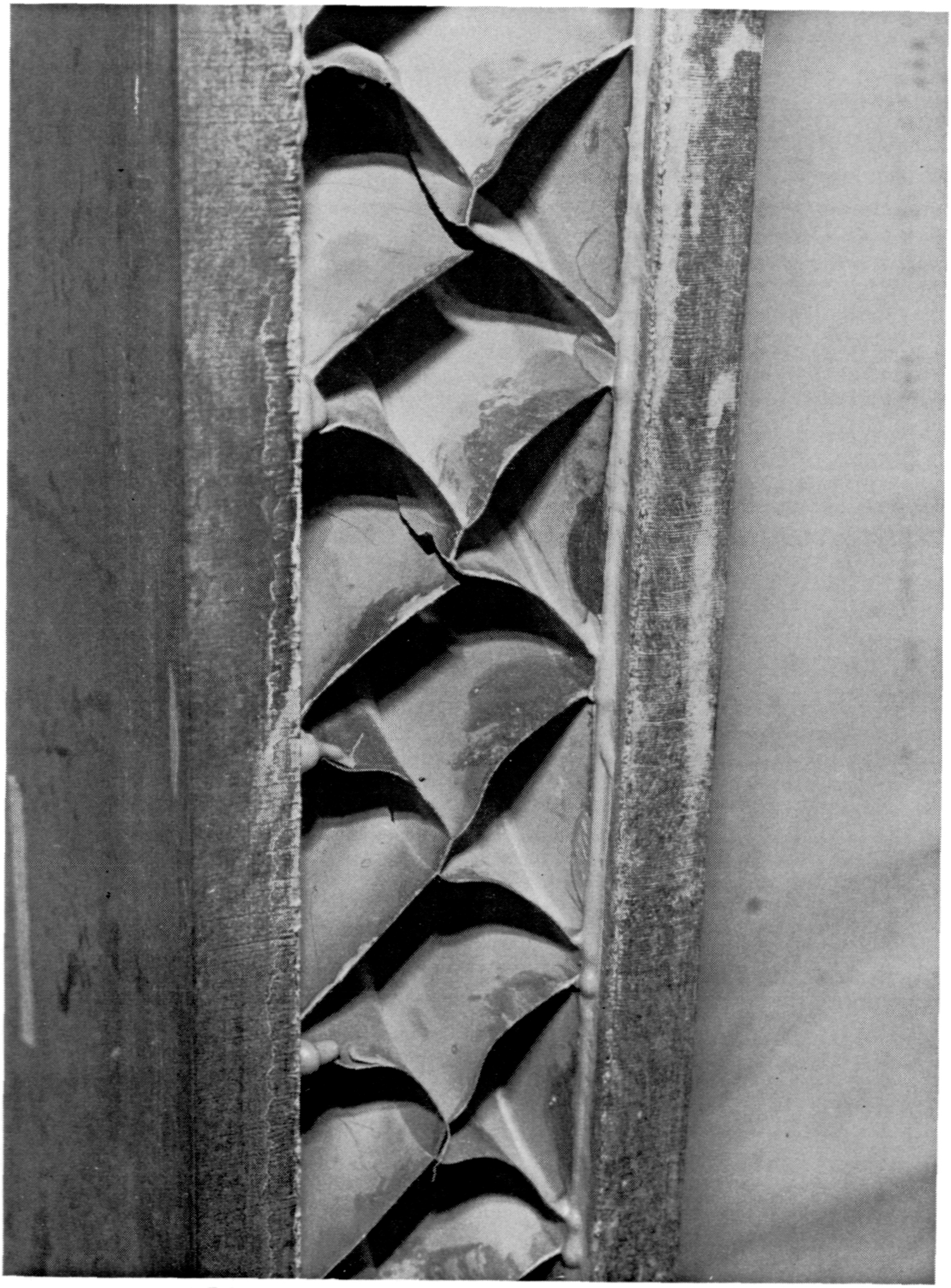


Figure 3-46. Transverse Core Shear Specimen

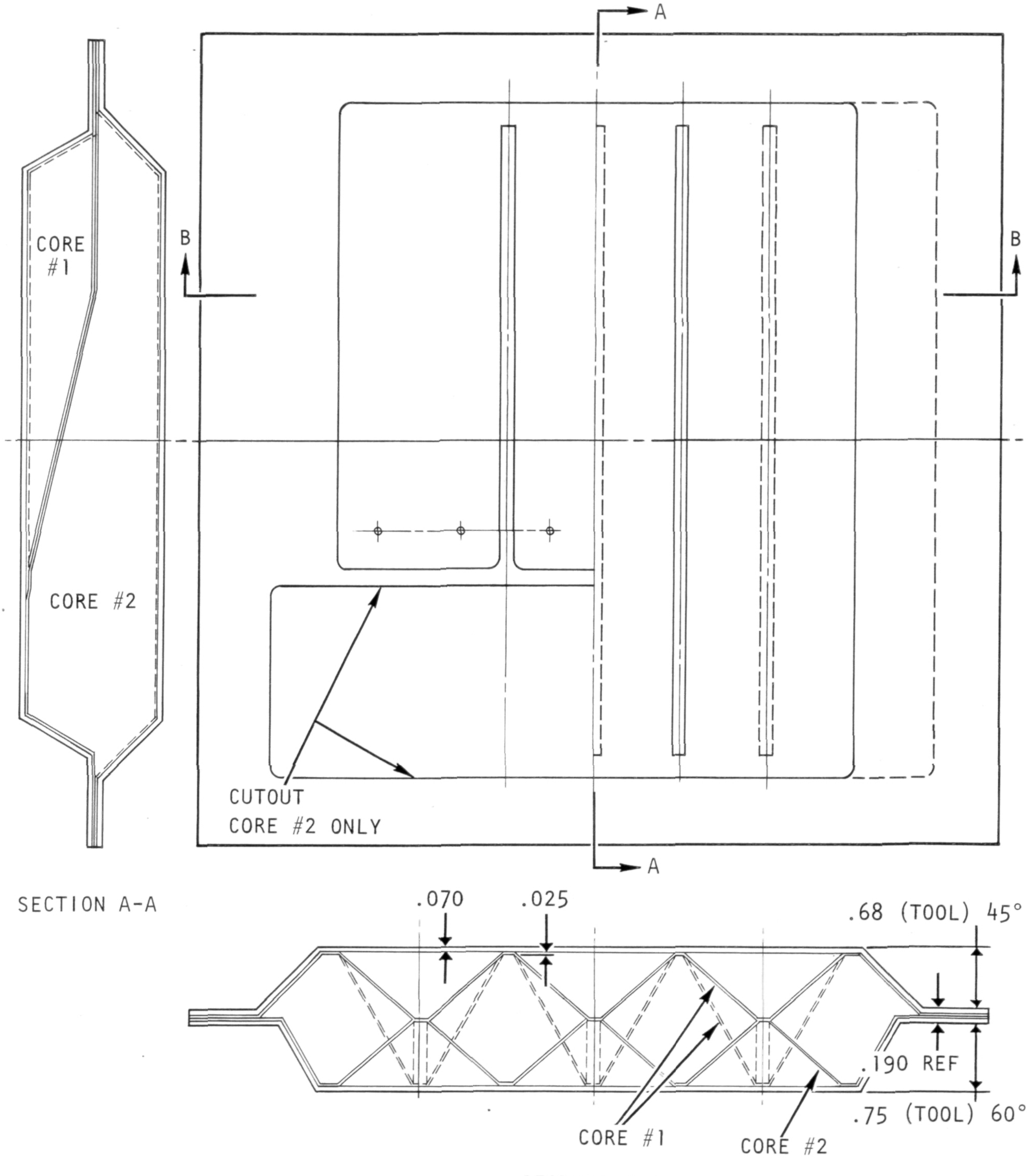


Figure 3-47. Straight Truss Core Panel

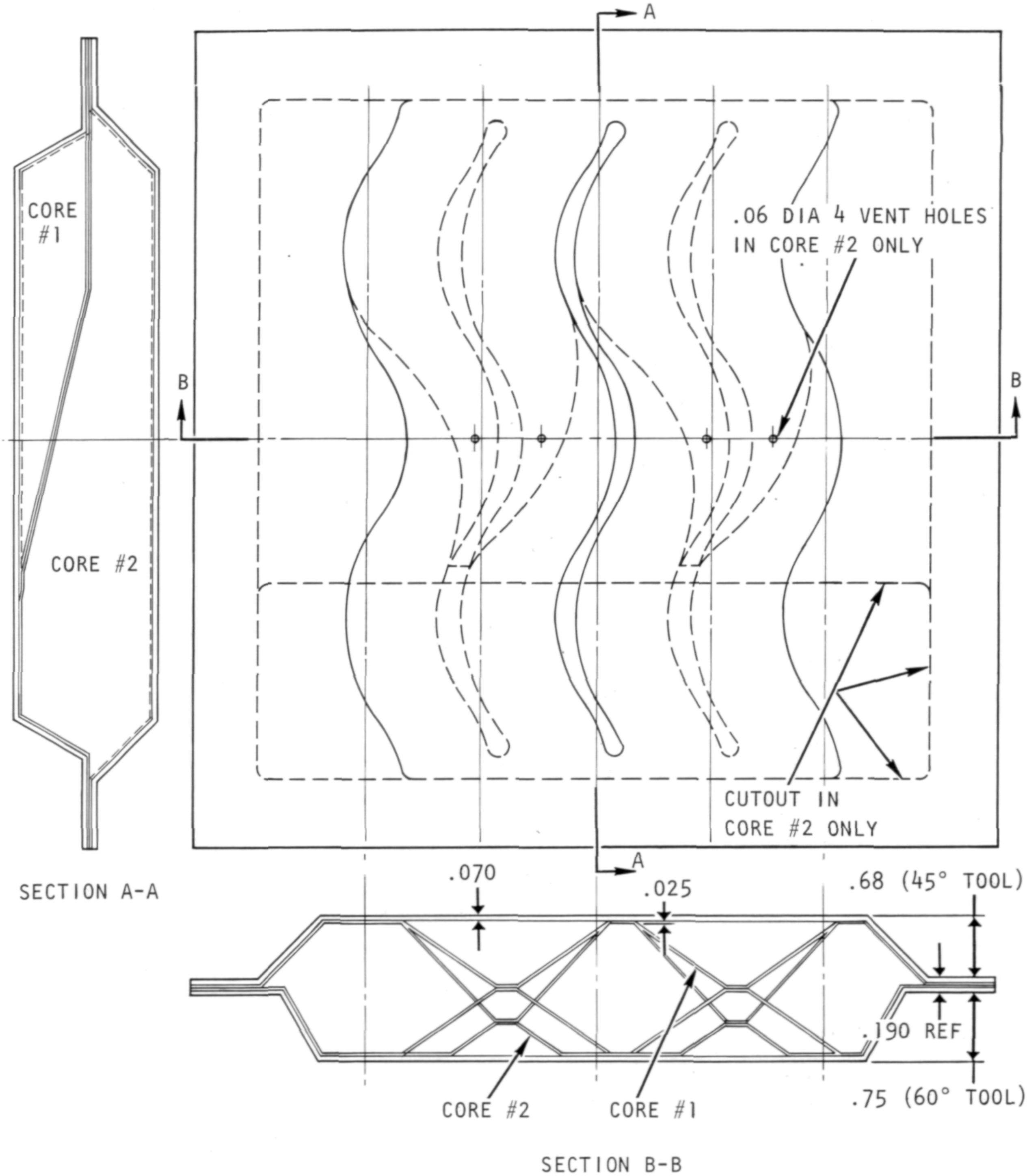


Figure 3-48. Sine Wave Truss Core Panel

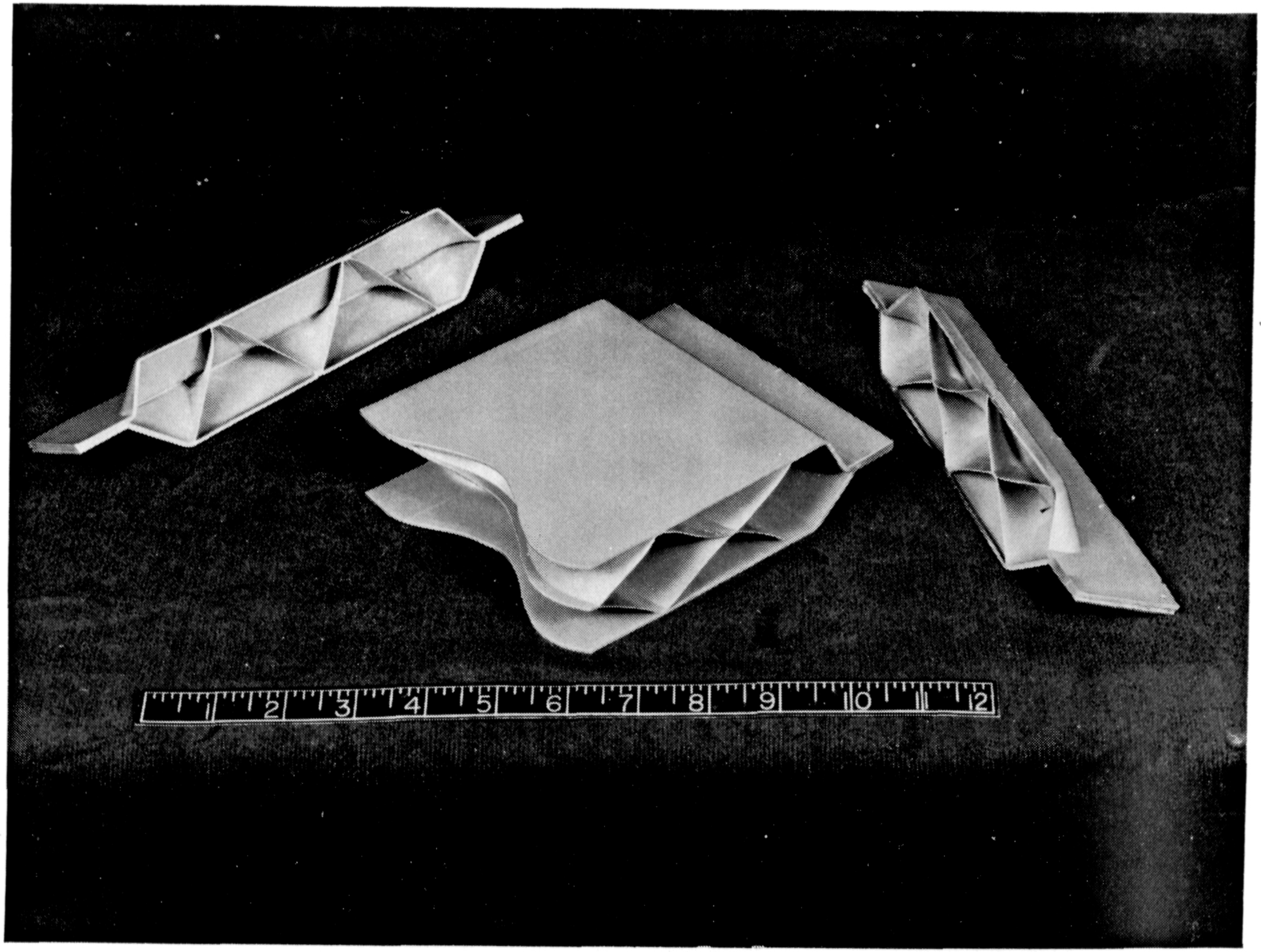


Figure 3-49. Core Transition Panel

Figure 3-50. Joint Test Specimen Assembly

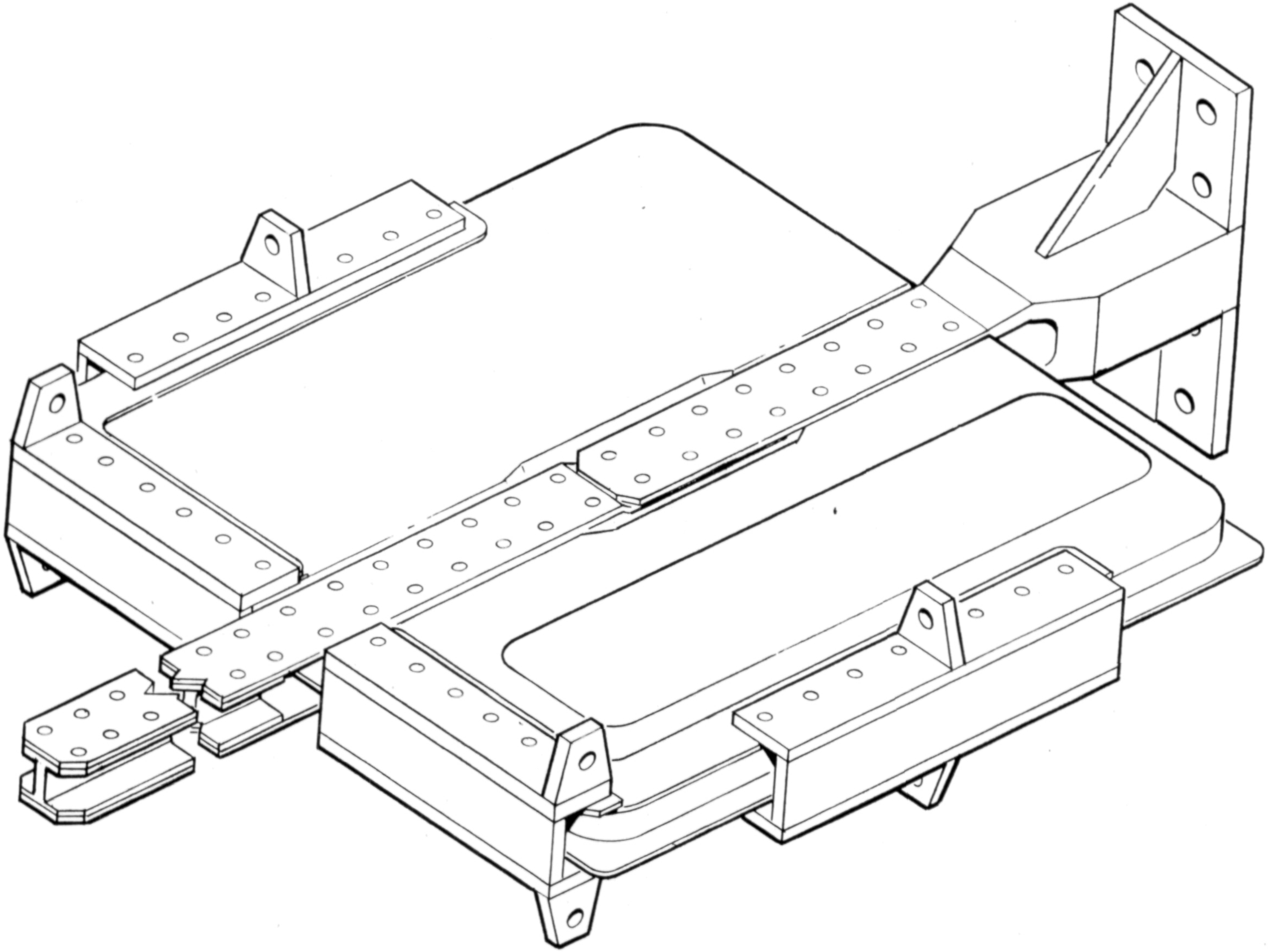


Figure 3-51. Joint Test Development Specimen

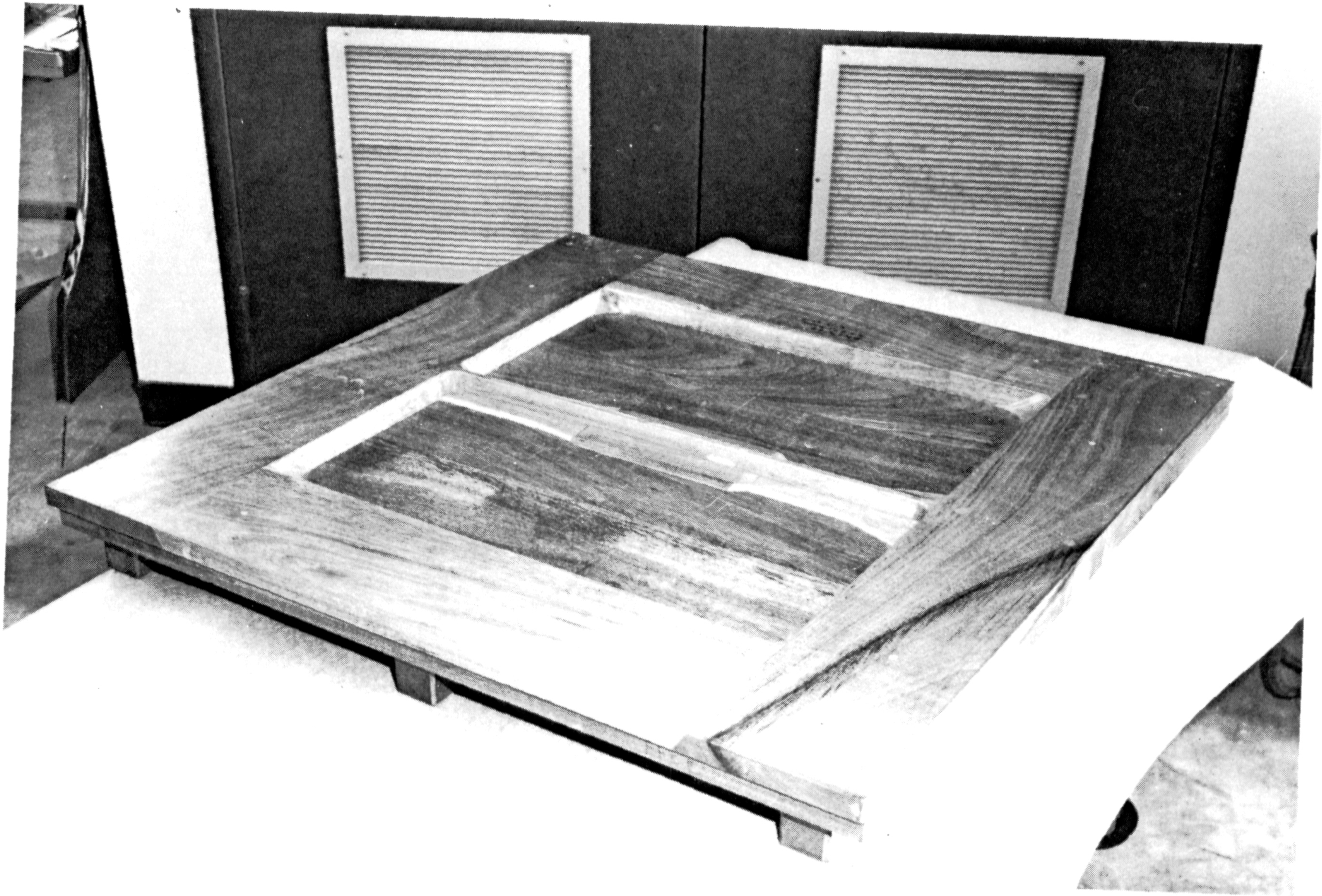


Figure 3-52. Tracer Pattern

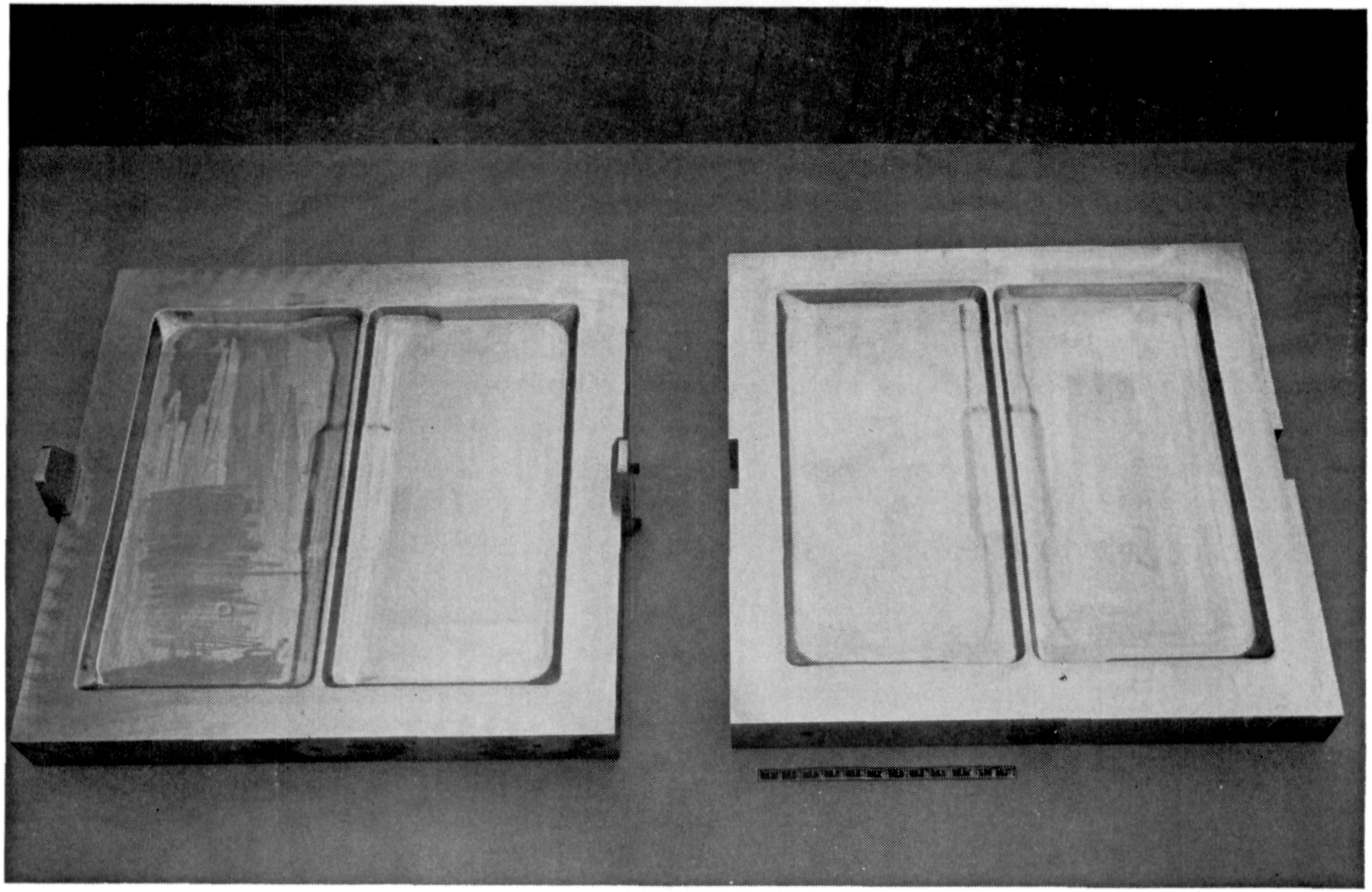


Figure 3-53. SPF/DB Tool Die

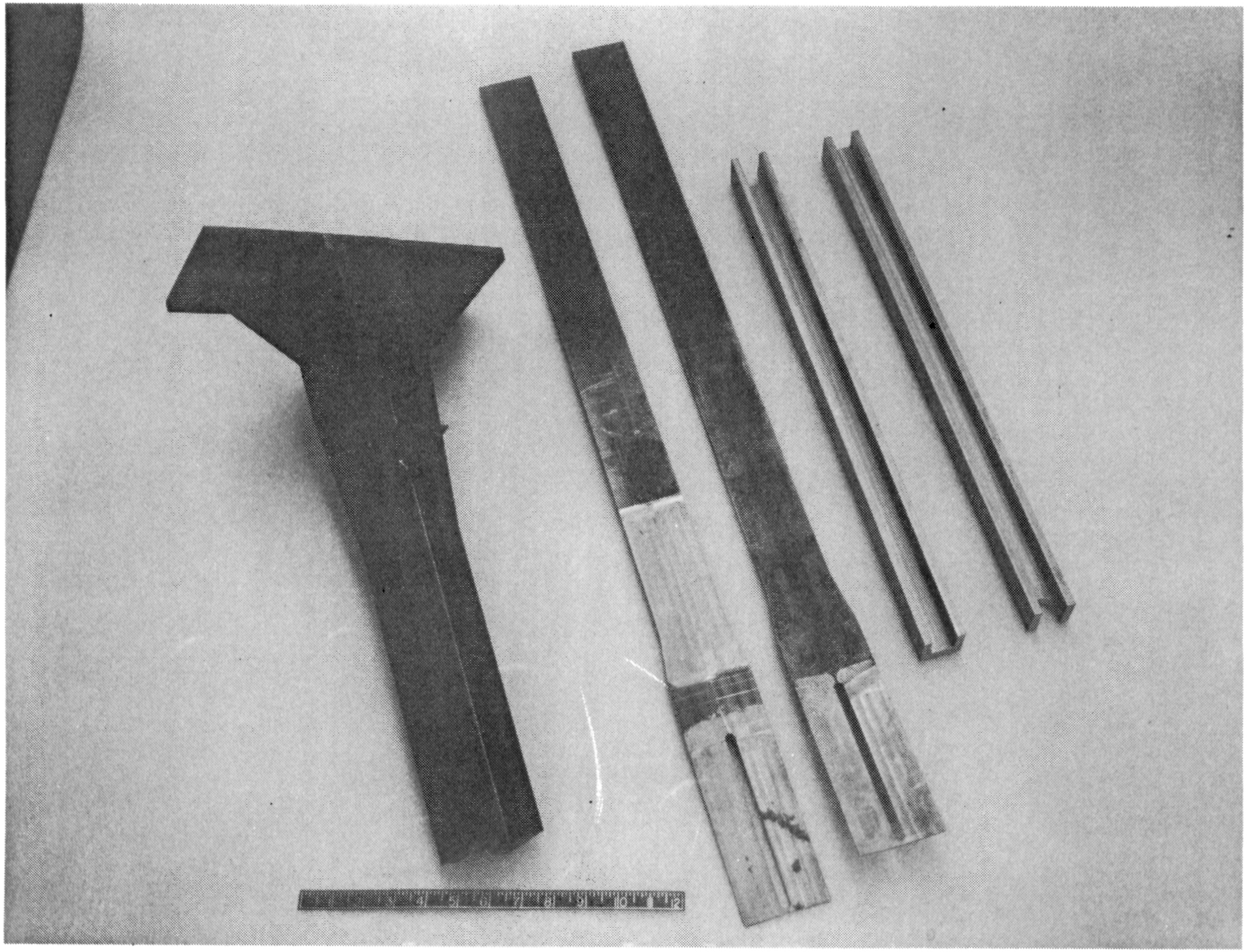


Figure 3-54. Test Development Specimen - Steel Details

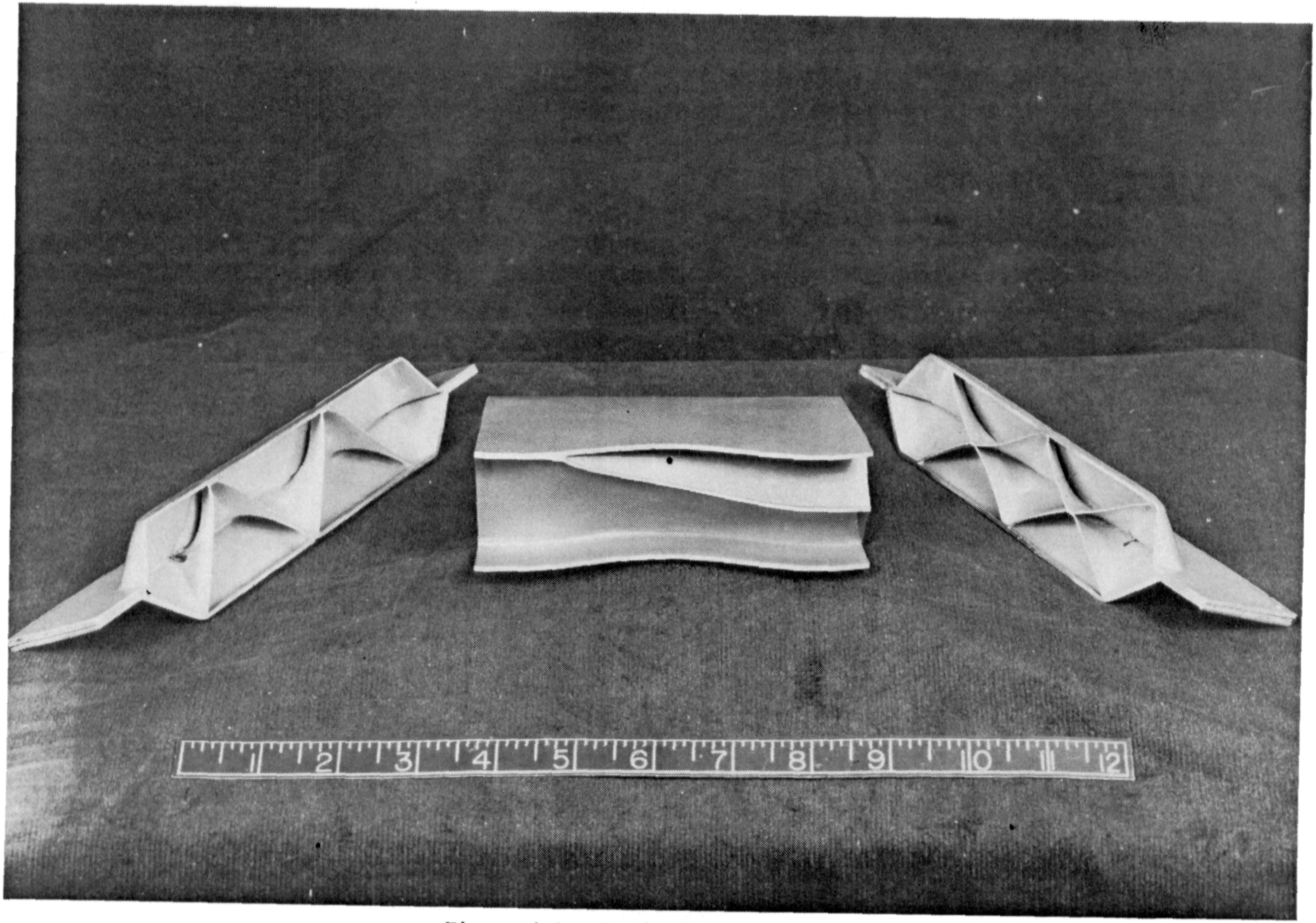


Figure 4-1. Producibility Panel

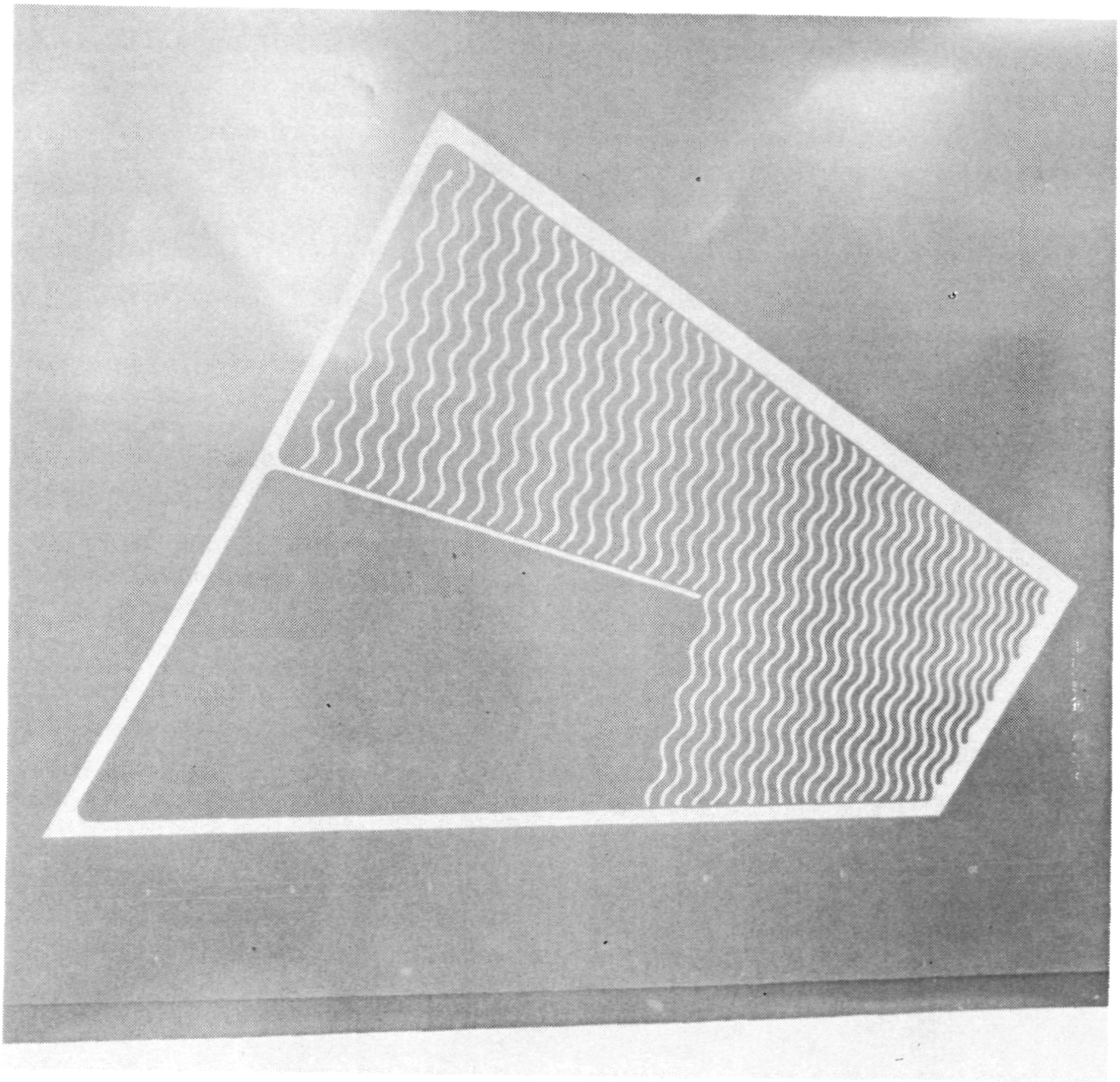


Figure 4-2. Stopoff Pattern

APPENDIX A

SPF/DB PROCESS

Titanium and some of its alloys exhibit unique characteristics at elevated temperatures which have permitted the development of the advanced technology of concurrent superplastic forming and diffusion bonding (SPF/DB). The optimum temperature for superplastically forming Ti-6Al-4V is 927° C (1,700° F). Fortunately, it is the same temperature used to diffusion bond titanium structures. Therefore, The SPF/DB processing of structure is accomplished during a single heat cycle.

In the SPF/DB process, mating surfaces are brought into intimate contact at elevated temperature. Atomic diffusion across the interface produces the bond. Test specimen bonds fabricated by using gas pressures in the SPF/DB process exhibit parent mental strength. Lap shear strength, for example, averaged 5.8 by 10^8 N/M2 (84,000 psi). Typical 6Al-4V shear strength is 5.4 by 10^8 N/M2 (78,000 psi).

Independent research at Rockwell International has now established three generic types of SPF/DB structures (figure A-1). In the first type, a superplastically forming sheet encounters titanium details, preplaced in the tooling, and is concurrently diffusion bonded to them. It is therefore possible to add functional members to the formed part. The procedure can also incorporate forming after bonding because both are done during a single process (heating) cycle.

The second type of SPF/DB structure - integrally stiffened - is made by simultaneous processing of two 6Al-4V sheets (figure A-1B). A stopoff compound applied to one sheet prevents bonding in discrete areas. The stopoff pattern corresponds to tooling cavities. When the pack reaches 927° C (1,700° F), pressure is applied and those areas not coated with stopoff are bonded. After bonding, gas pressure is introduced which superplastically forms the unbonded areas. Some of the variations possible are shown in figure A-2.

By using selective bonding and three sheets, the SPF/DB process yields the most advanced form of hardware - expanded sandwich (figure A-1C). A variety of demonstration SPF/DB sandwich structures has been fabricated. Two important advantages of SPF/DB sandwich can be cited:

1. The external configuration of the fabricated part is obviously determined by the tool cavity and may be a design variable. On the other hand, the core configuration is determined by the stopoff pattern; it may be of infinite variety and can be modified without tooling change.

2. The process inherently provides an integral edge closure. This avoids what is frequently a significant cost factor in applying conventional honeycomb sandwich. Figures A-3 and A-4 show typical representative core configurations that have been fabricated to date, including a truss core, dimpled core (core bonded to face sheets in an intermittent spot pattern), and sine wave core (core bonded in a parallel sine wave pattern). The process also readily permits core variations within the same panel; i.e., all types of core can be used within the same panel by varying the stopoff pattern if an advantage can be gained with this approach.

TEST PLAN

The core shear properties used in this analysis were based on a limited number of test specimens from the ongoing IR&D test program. Reliable data cannot be obtained from such a small number of test specimens. Therefore, additional testing was planned, as part of task 3, to develop analytical methods and data base for multicore SPF/DB sandwich.

Variations of the depth, sine wave radius, and core thicknesses as indicated by the core trend analysis will be incorporated in fabrication of the test panels. The number of specimens for different tests such as short column, compression, and beam bending are summarized in tables A-I through A-III.

The joint development specimen consists of a steel cantilever beam assembly which is fixed to the test support structure with eight tension bolts. The straps that run outboard beyond the panel are used as loading structures. Four weld assemblies are fastened along the periphery of the panel to introduce vertical and moment loads. The specimen sizing and loading corresponds to T-38 horizontal stabilizer critical condition. The objective of the test is to determine the behavior of the joint between the titanium SPF/DB sandwich and steel fitting. All strain gages are to be calibrated and identified prior to testing as shown in figures A-5 and A-6. The load V_Z, and M will be applied to the specimen in 20-percent increments up to 60-percent and V_Z and M and 10-percent increments thereafter, up to failure, with deflection and strain gage readings taken at each increment. All significant data, test effort, and observation analyses will be recorded.

MANUFACTURING PLAN

MANUFACTURING OPERATION

The manufacturing operation involves the fabrication of five horizontal stabilizers for the T-38 aircraft to consist of one each process verification part, static test part, left horizontal stabilizer, right horizontal stabilizer, spare,

The proven techniques of the SPF/DB titanium fabrication process will be used as established by past experience and by the producibility verification parts fabricated in task I. Equipment, tool concepts, basic time, pressure, and temperature profiles will be modified to meet the requirements of this program. The SPF die tool will be developed from basic line data furnished by Northrop. Actual plaster masters will be used, if available. The SPF/DB die material will be 22-4-9 stainless steel and will be contour machined into the desired configuration and simplified to minimize tool fabrication costs. An upper and a lower container of mirror image will be used.

All titanium sheet and plate material will be sized and prepared for the forming operation by NAAD Materials and Producibility personnel using production equipment, as necessary. The same is true of all processing with the exception of chem-milling and spindle line boring, which will be done by outside vendors.

SPF/DB processes will be controlled by manufacturing process procedures (MPP's) following the requirements of an engineering material process specification (MPS) and will be prepared by Materials and Producibility personnel in conjunction with manufacturing engineering and quality personnel. Manufacturing operation record (MOR) books will be prepared for each stabilizer. These documents will provide a permanent record of each process control step and detail part in order to provide an in-process inspection record.

Machined parts will be purchased in the finished machine condition. Drilled holes for fasteners will require construction of a localized drill plate tool for air-feed drilling.

Existing facility and equipment will be used for fabrication of the horizontal stabilizer. The SPF/DB die is of the size that either the 4,500 or the 7,000-ton hydraulic press can be used. Electrical heater power supplies and the required gas plumbing are available. Existing air-guide mobile tool transfer platens will be used for handling the relatively large tool involved. Although the fabrication will be controlled by Materials and Producibility, all SPF/DB cycling will be done in production equipment.

A typical simplified flow diagram for the SPF/DB process is shown in figure A-7. The T-38 horizontal stabilizer will be produced generally in accordance with this flow sheet.

FACILITIES AND EQUIPMENT

The facilities and equipment to be used in the fabrication of the T-38 horizontal stabilizers are at the NAAD facility. An area of 30,000 square feet containing the hydraulic presses will be used for tool buildup and the SPF/DB cycle operation. Either the 4,500- or the 7,000-ton press will be used. The 4,500-ton press, along with one of the air-guide transporters, is shown in figure A-8.

The silk screen method of placing the stopoff pattern on the sandwich core sheets will be performed on existing production facilities. However, a backup source has been established with outside vendors.

Chem-milling requirements will be accomplished by means of purchased labor from local suppliers such as Aerochem, of Orange, California.

TOOL DESIGN AND FABRICATION

The tool design function for this program will detail the tool concept envisioned and shown on the manufacturing flow chart. Fully dimensioned tool drawings will convey required information to the tool fabrication shop. Stop-off patterns on Mylar and rubylith will be produced in conjuncation with metal templates and proper alignment systems.

The stabilizer airfoil mold line will be developed on a computer graphics system, and section cuts on Mylar will be delivered to the tool fabrication shop. Rubylith stop-off patterns will be prepared on the same system for automated cutting on a Gerber plotter.

Tool fabrication will be accomplished in NAAD's machine shop area. Two tools, one upper and a lower die cavities, will be machined from 22-4-9 stainless steel heavy plate in accordance with the detailed tool design. Silk screens for application of yttria stop-off material will also be fabricated in-house.

SCHEDULING

The T-38 horizontal stabilizer program consists of three tasks covering the time period from August 1979 through December 1981. The master program schedule, shown in figure 2-1, depicts the time-phased relationship of all major activities and events required to execute this program.

QUALITY ASSURANCE PLAN

The quality program Rockwell North American Aircraft Division (NAAD) is an integration of a number of systems and procedures operation within and across the functional organizations responsible for producing a quality product. All elements requisite to meeting quality assurance requirements outlined in MIL-Q-9858A, MIL-STD-1520A and MIL-C-45662A are established management practices at NAAD.

Among the significant features included in the quality assurance program are (1) a drawing and change control system, (2) approved procedures for disposition of nonconforming supplies and procedures for correcting system deficiencies which cause or contribute to these conditions, (3) a program for calibration and certification of measuring, test equipment, and tooling used as inspection media, (4) a formalized program to prevent foreign object damage (FOD) in delivered products, (5) a system for approving special processes, (6) procedures for selecting and controlling suppliers, (7) training and certification of personnel who perform key tasks throughout the manufacturing phase, (8) conducting progressive inspections and inspections at strategic points in the manufacturing process, (9) monitoring quality trend performance of the various manufacturing functions, and (10) auditing operations having an influence on product quality for conformance to established procedures.

The features enumerated in the preceding paragraph show that the NAAD quality program is sufficiently broad in scope to provide cost-effective quality-program services for a wide variety of program types, ranging from large aircraft programs to small research programs. These features of the NAAD quality program will be applied in the varying degrees necessary to assure accomplishment of the program objectives and end-item requirements.

The Quality Assurance (QA) division director, reporting to the NAAD Operations vice president, is responsible for functional policy. He has final jurisdiction in all matters involving quality of workmanship and the conformance of products and materials to specifications, drawings, and standards, and to contractual quality and reliability requirements. He is responsible for assuring that quality and reliability requirements and policies are implemented.

The QA organization contains the necessary elements to provide an effective relationship with those functional groups most concerned with product quality; namely, Engineering, Material, and Manufacturing. The organization consists of the following four major sections:

1. Product Inspection - NAAD onsite inspection of manufacturing activities through final delivery

2. Procurement Quality Control - Approval and surveillance of suppliers' quality control systems and performance of source receiving and shipping inspection

3. Quality Assessment and Planning - Quality planning, analysis, and material review and corrective action system

4. Quality Engineering - Laboratory support to aid in control of production processes, new material and process development, calibration control of measuring instruments and devices, and development of statistical and general quality control methods

REQUIREMENTS

DRAWINGS, SPECIFICATIONS, AND CHANGES

The data control system includes a change verification record (CVR) and a method for identifying assemblies, verifying that design changes to parts have been accomplished. These records list changes affecting an assembly. Each change which has been satisfactorily incorporated is verified by inspection personnel.

MEASURING AND TEST EQUIPMENT

Measurement and test equipment used for product acceptance is inspected for visual, dimensional, and operational characteristics as applicable when initially received and at periodic intervals thereafter. Each item is marked to indicate the date when the next inspection is required and the stamp or signature of the person who made the last inspection. Equipment records reflect the same information.

The necessity for and frequency of periodic inspections are based on objective evidence of the stability and continued accuracy of the equipment as derived from the historical data for each item.

All measurement and test equipment used to check product components and systems, to check materials that are used in a product, or to check control of the processing of a product is checked against a standard having greater accuracy. The required accuracy of shop test and measurement equipment is one-fourth the tolerance of the most precise tolerances of any item required to be checked by the equipment.

The standards against which test and measurement equipment is periodically checked have their accuracy verified directly by, or through precise comparison with, legal standards traceable to the National Bureau of Standars for domestic procurements, or comparable authorized standards for foreign procurements.

TOOLING USED AS MEDIA OF INSPECTION

The NAAD special tooling controls include a requirement for initial inspection of dimensional special tooling (DST) built by NAAD. Continued accuracy of DST, used as a media of inspection during its production use, is assured through established periodic reinspection intervals. Results are recorded on a periodic inspection record maintained in the using department. Tools requiring such controls are entered in the Calibration Recall Information System (CRIS) to assure automatic notification of the required reinspection and the necessary follow-up to assure completion.

INSPECTION AND TEST

All phases of processing, fabrication, assembly, and test are under constant surveillance for compliance to specifications and for functional integrity. Major areas of onsite product inspection are described in the following paragraphs. These inspections are performed progressively and at strategic points in the manufacturing process.

Production Work Orders and Records

Manufacturing Orders describe methods of manufacturing detail parts and minor subassemblies. The orders contain information such as type of material, quantity to be made, sequence of fabrication and processing operations, and inspection callouts. (MOR) books are used for manufacturing and inspection records on major assemblies and on end items consisting of multiple assemblies. These documents are issued by Manufacturing after approval by Q&RA.

Tooling

Tools used for product control are checked periodically by Inspection personnel located in the using manufacturing department. Individual parts, and the templates used in their fabrication, are also checked and recorded by Inspection personnel.

Detail Parts and Assemblies

Materials used in detail sheet metal and machined parts fabrication are checked for specification conformance. Manufactured parts are also examined by nondestructive test methods and visually inspected for defects, damage, and quality of workmanship. Inspectors use templates, gages, check fixtures, meters, instruments, or other appropriate inspection and testing devices which have been prechecked or qualified by Q&RA.

During production of subassemblies and assemblies, Q&RA performs inspection operations at specified intervals and sequences to verify conformance to design.

Process Control

NAAD assurance of process control is achieved through established measures such as acceptance of procured processing from approved sources only (when the process is one requiring approval), assuring NAAD capability to perform processes, monitoring processing operations and the operation and maintenance of processing equipment, and providing technical interpretation of processing requirements.

RECORDS

The NAAD Quality Assurance Program contains provisions for initiating and maintaining records essential to management of the various aspects of product quality. Included are records such as the following:

- Receiving Report
- Receiving Inspection Instruction Card
- Manufacturing Order
- Manufacturing Operations Record (MOR)
- Change Verification Records (CVR)
- Material Review Disposition (Form 23-H-1 or equivalent)
- Discrepant Material Disposition (DMD)
- Parts Replacement Request (PRR)
- 54T Cards (First Article Inspection Form)
- Inspection Stamp Control Records
- Personnel Certification Records
- Preventive Action Requests

INDICATION OF INSPECTION STATUS

Inspection stamps are used to indicate that material, tools, parts, and assemblies have been tested and accepted, withheld or rejected. The use and control of stamps is established by existing procedures. Records of the assignment of all inspection stamps are maintained by Q&RA. Stamp impressions are placed adjacent to the part number on each item, unless such stamping is not feasible because of limited space or is specifically prohibited by the drawing or applicable specification. In such cases, the Q&RA acceptance status is indicated by stamping a tag affixed to the item. Stamps are also used on related documents, such as receiving reports, Manufacturing Orders, Manufacturing Operations Records, and Change Verification Records.

CONTROL OF RAW MATERIAL

Raw materials received are inspected and tested to verify conformance to purchase order and design requirements. Material is inspected for identification, damage, markings, finish, and proper packaging. Applicable chemical analysis and physical test reports are analyzed by Receiving Inspection to determine conformance to specifications. Laboratory tests are conducted where appropriate to assure conformance.

IDENTIFICATION, HANDLING, AND STORAGE OF MATERIAL

Raw materials and other components of deliverable products are identified with appropriate markings to assure adequate control and indication of change incorporation status throughout the manufacturing process. Handling and storage controls are established to provide appropriate protection of work-in-process materials as well as completed products awaiting shipment.

CONTROL OF SELLER'S PROCUREMENT SOURCES

Quality control requirements are transmitted to suppliers by special quality specifications which include pertinent processing requirements. Factors in the selection of suppliers are their conformance to the specified QA requirements, supplier's quality history, and the results of quality surveys. The surveys are conducted when NAAD has had no recent experience with a potential supplier. After selection, surveillance is maintained over the supplier's QA system and inspection procedures to insure continued conformance. All purchase requests, advance purchase orders, and specifications to be transmitted to suppliers are reviewed to insure inclusion of the necessary QA requirements. Items recieved at NAAD are inspected and tested to verify conformance to purchase order and design requirements. Source inspection is performed when it is considered economical.

Chem-milling and spindle-line boring are expected to be purchased services on this program.

PRESERVATION, PACKAGING, PACKING, AND SHIPPING

Shipping inspection insures that (1) nonflyaway articles are complete and in accordance with drawings and specifications, and that necessary tests have been accomplished, (2) preservation, packaging and packing are adequate, (3) shipping containers are legibly and correctly marked, and (4) adequate records and shipping documents are prepared for each item.

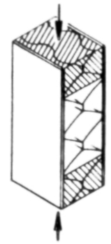
NONCONFORMING SUPPLIES

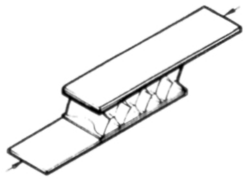
Detail parts found by Inspection to depart from engineering drawings and specifications are withheld for disposition before further processing.

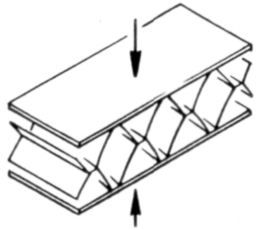
Those items that can be completed or reworked to meet requirements are documented as such on the Manufacturing Order and returned to Manufacturing.

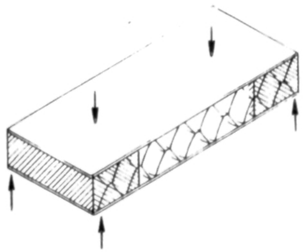
Table A-I

SPF/DB MULTICORE TEST MATRIX (DEPTH 1.25)









Depth mm (in.)	Radius mm (in.)	Core mm (in.)	Short Column		Core Shear		Flat Comp.	Bending Beams
			Long	Tran	Long	Tran		
31.75 (1.25)	25.4 (1.0)	.64 (.025) .81 (.032) 1.27 (.050)						
	38.1 (1.5)	.64 (.025) .81 (.032) 1.27 (.050)	2	2	2	2	2	
	50.8 (2.0)	.64 (.025) .81 (.032) 1.27 (.050)						
	∞	.64 (.025) .81 (.032) 1.27 (.050)	2	2	2	2	2	

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Table A-II

(SPF/DB MULTICORE TEST MATRIX (152 ELEMENTS) (DEPTH 1.75)

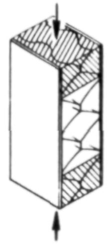
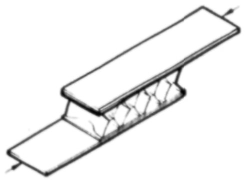
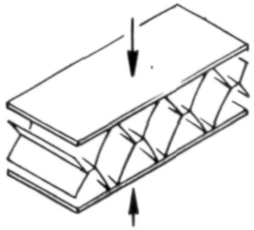
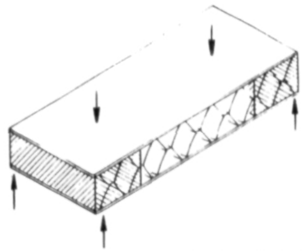
			Short Column		Core Shear			
								
Depth mm (in.)	Radius mm (in.)	Core mm (in.)	Long	Tran	Long	Tran	Flat Comp	Bending Beams
44.45 (1.75)	25.4 (1.0)	.64 (.025) .81 (.032) 1.27 (.050)	2	2	2	2	2	
	38.1 (1.5)	.64 (.025) .81 (.032) 1.27 (.050)	3 3 3	3 3 3	3 3 3	3 3 3	3 3 3	3 3 3
	50.8 (2.0)	.64 (.025) .81 (.032) 1.27 (.050)	2	2	2	2	2	2
	∞	.64 (.025) .81 (.032) 1.27 (.050)	2 2 2	2 2 2	2 2 2	2 2 2	2 2 2	2 2 2

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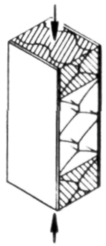
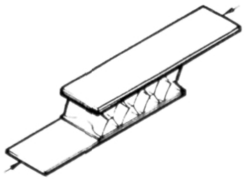
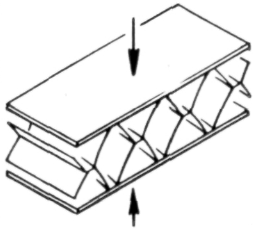
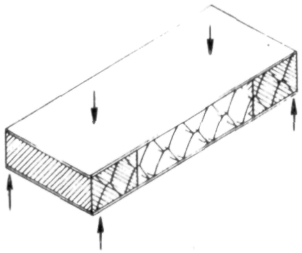
Table A-III

SPF/DB MULTICORE TEST MATRIX (DEPTH 2.5)

Depth mm (in.)	Radius mm (in.)	Core mm (in.)	Short Column Long	Short Column Tran	Core Shear Long	Core Shear Tran	Flat Comp	Bending Beams
63.5 (2.5)	25.4 (1.0)	.64 (.025) .81 (.032) 1.27 (.050)						
	38.1 (1.5)	.64 (.025) .81 (.032) 1.27 (.050)	2	2	2	2	2	
	50.8 (2.0)	.64 (.025) .81 (.032) 1.27 (.050)						
	∞	.64 (.025) .81 (.032) 1.27 (.050)	2	2	2	2	2	

Total Specimen = 152

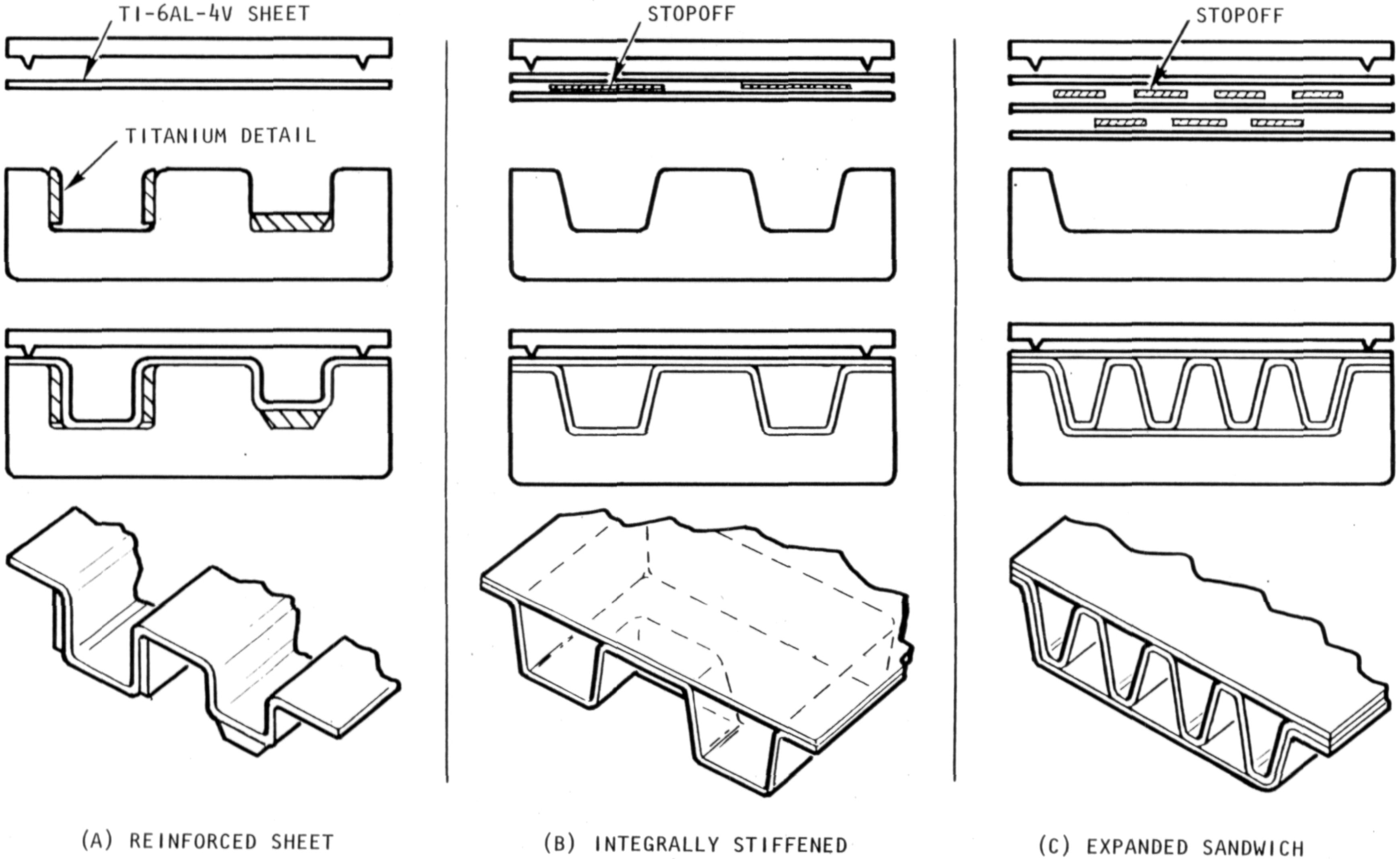


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Figure A-1. Three Basic Types of SPF/DB Structure

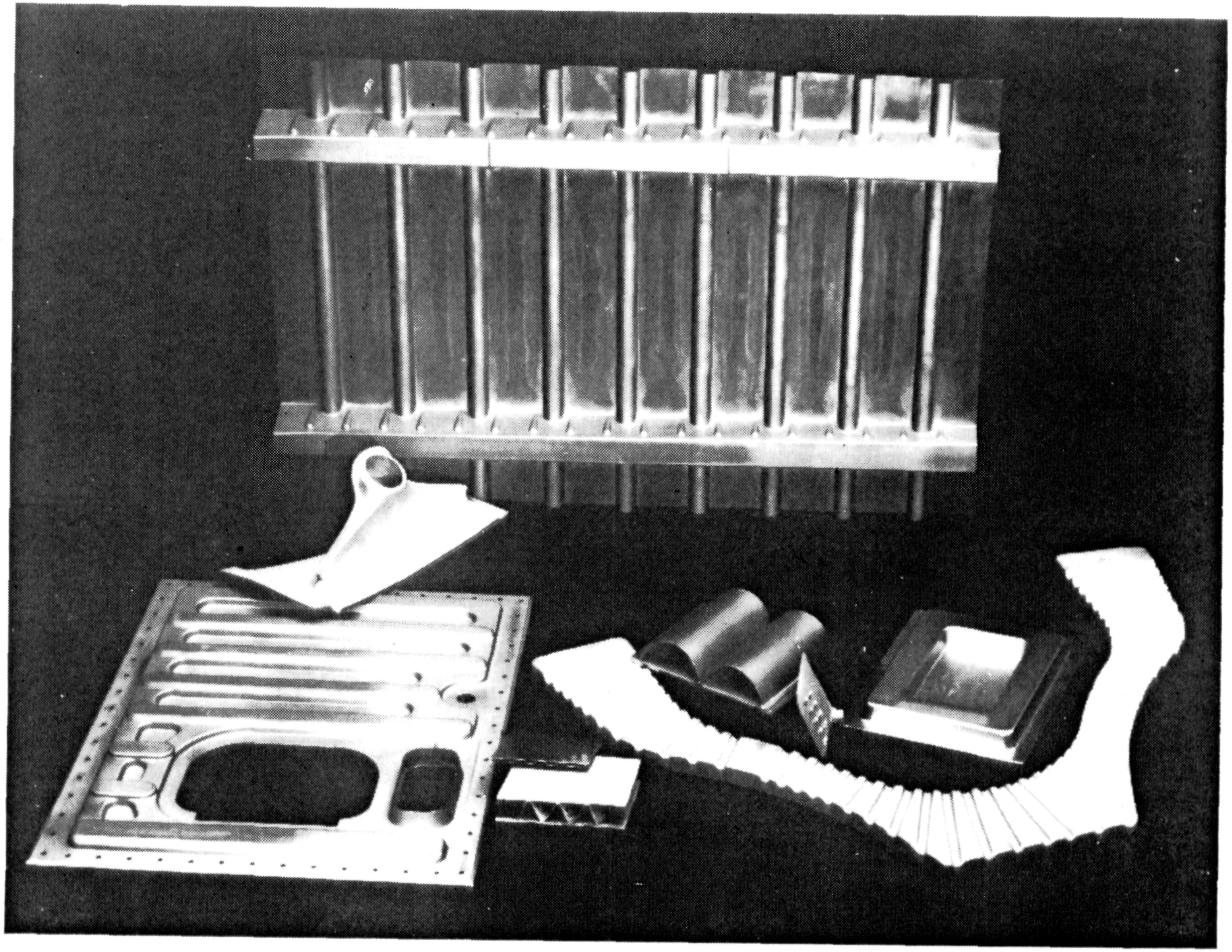

Figure A-2. Two-Sheet Technology Fabrication Variations

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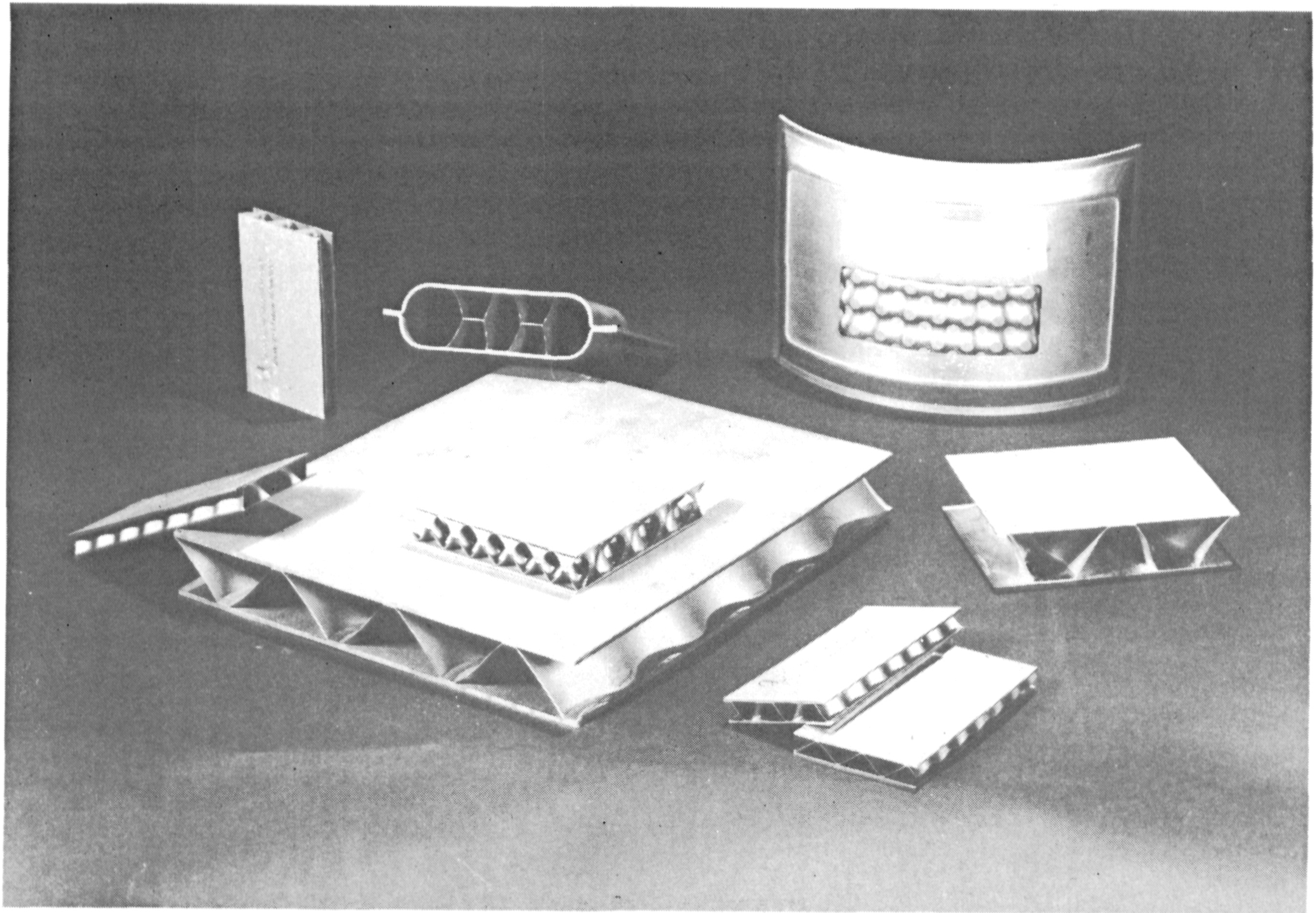

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Figure A-3. SPF/DB Sandwich Variations

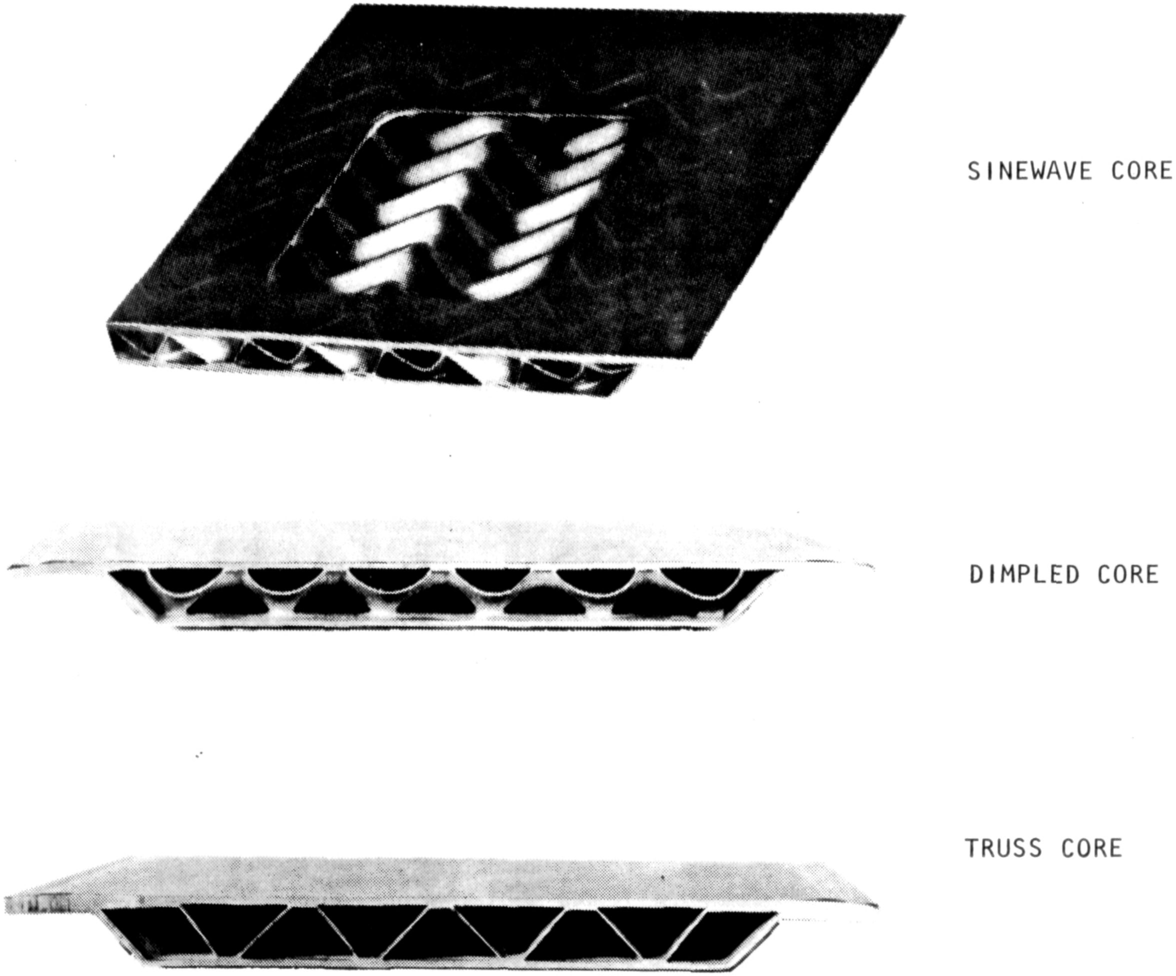

Figure A-4. SPF/DB Sandwich Variations

TYPE OF LOADING:	COMPLEX LOADING
SPECIMEN SIZE:	559 BY 559 MM (22 X 22 INCHES)
NO. OF SPECIMENS:	ONE
NO. OF ROSETTS:	ONE ROSETTE INSTALLED ON SPINDLE FITTING ON COMPRESSION SIDE
STRAIN GAGES:	• SIX ROSETTS INSTALLED ON PANEL COMPRESSION SIDE BETWEEN TWO CONSECUTIVE NODES • ONE ROSETTE INSTALLED ON SPINDLE FITTING ON TENSION SIDE BACK TO BACK WITH ROSETTE = 1. • TWO ROSETTES INSTALLED ON PANEL TENSION SIDE BETWEEN TWO CONSECUTIVE NODES BACK-TO-BACK POSITION AS ROSETTES = 2, 3.

LOCATION	ESTIMATED APPLIED LOAD V_Z NETWON (LB)	ESTIMATED APPLIED MOMENT M N-m (LB-IN.)
A	3,470 (780)	668 (5,915)
B	6,316 (1,420)	1,011 (8,950)
C	4,404 (990)	681 (6,030)
D	3,603 (810)	276 (2,440)
E	8,896 (2,000)	276 (2,440)

Figure A-5. Test Plan

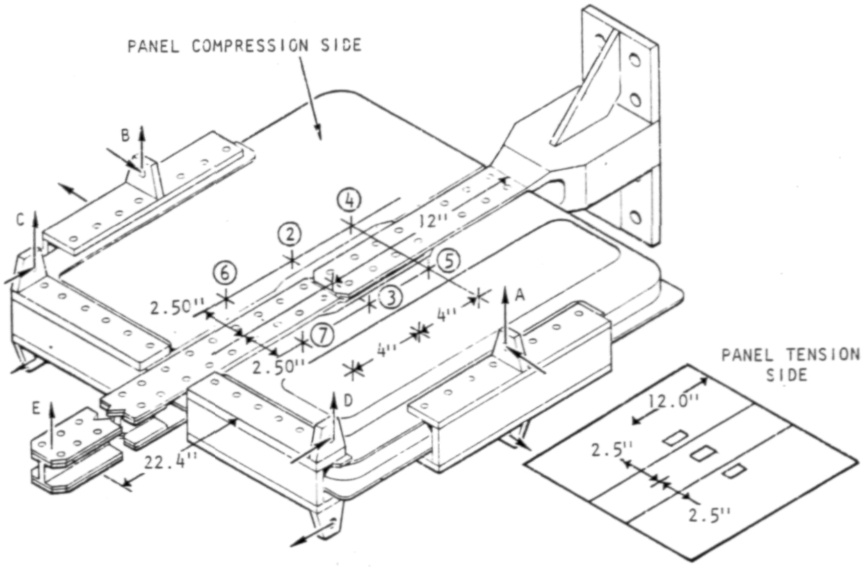

Figure A-6. Panel Compression

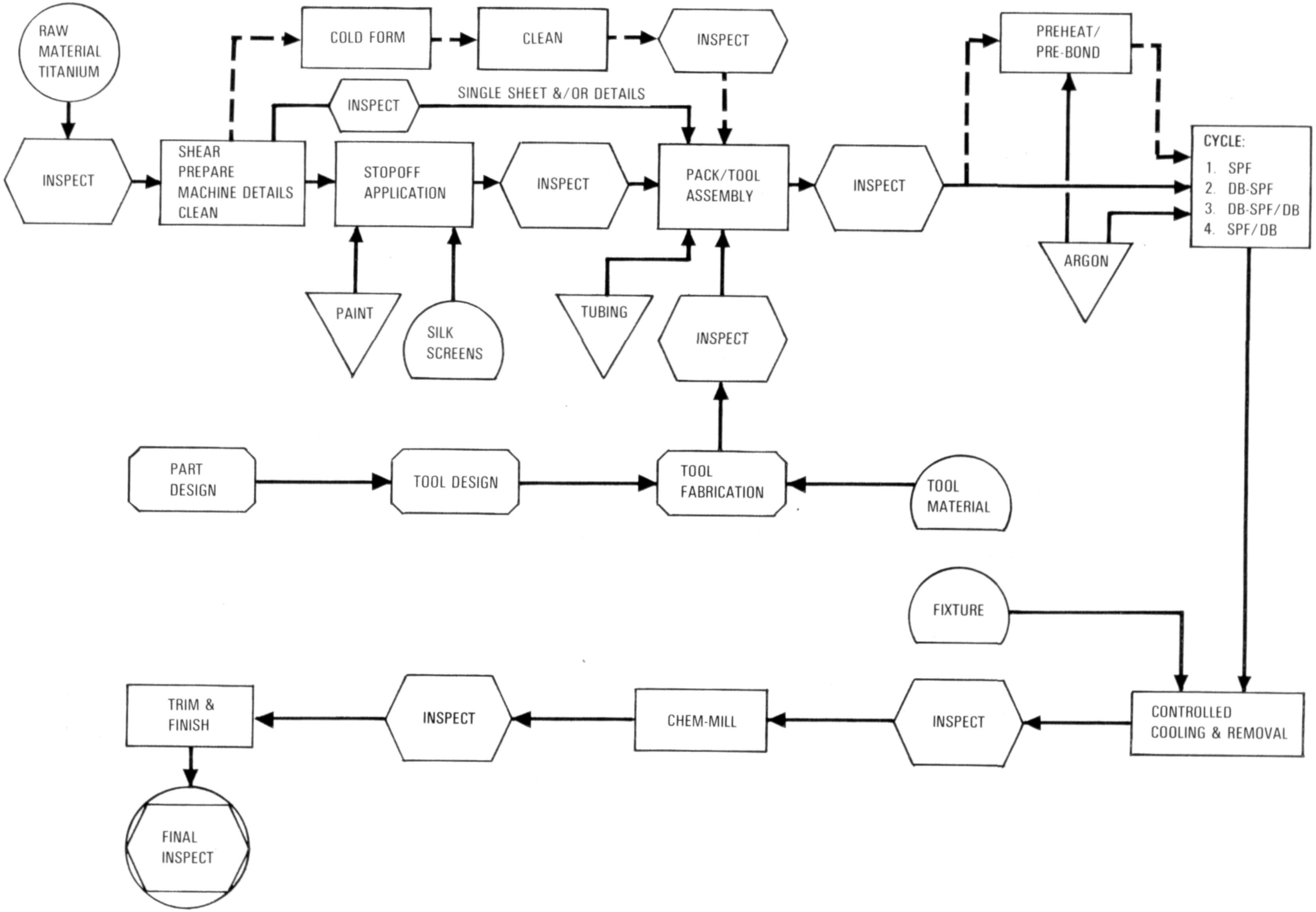

Figure A-7. Flow Diagram SPF/DB Process

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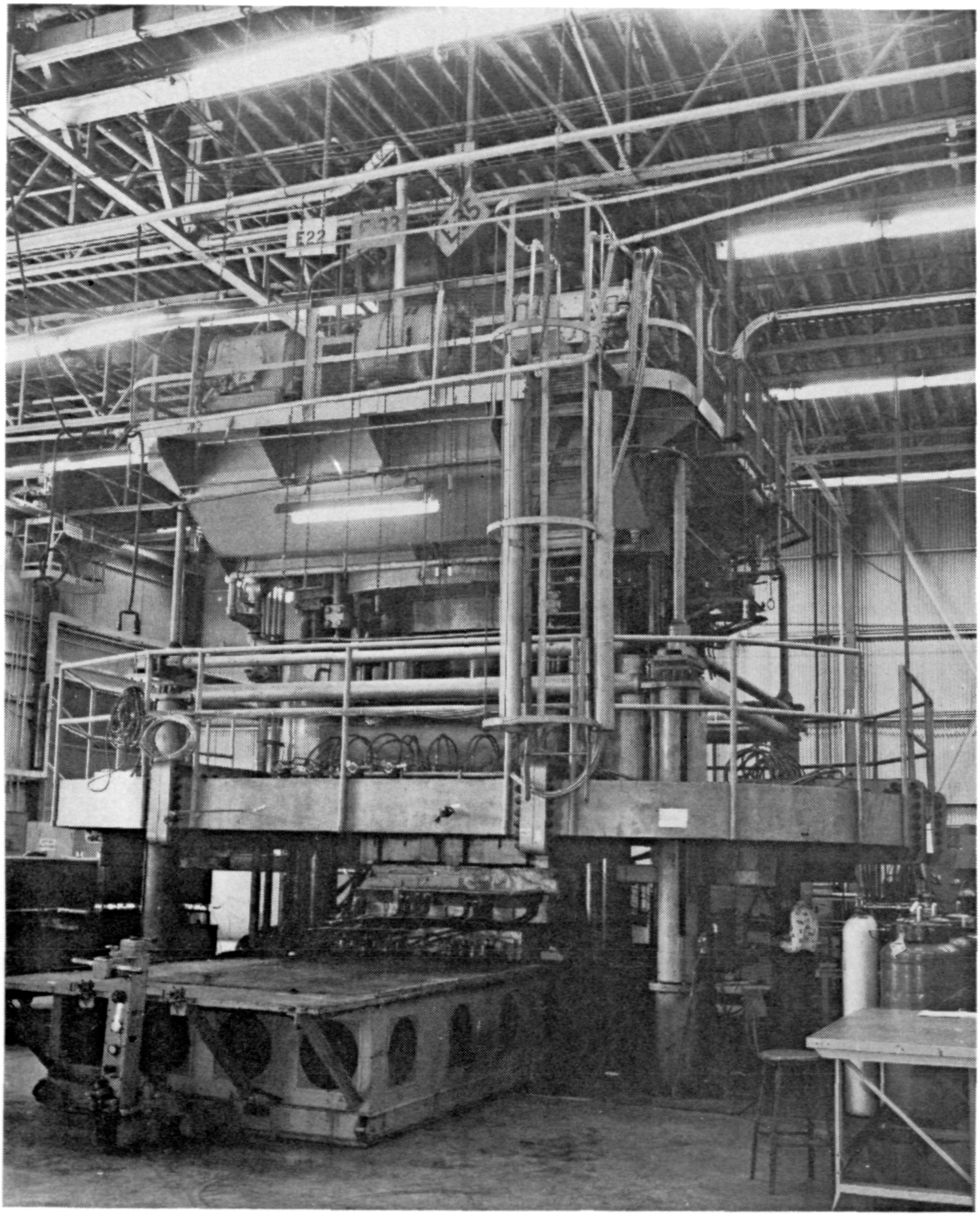

Figure A-8. A 4500-Ton Press in a Diffusion Bonding Facility

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16. Abstract

This program was conducted to demonstrate the structural integrity and potential cost savings of superplastic forming/diffusion bonding (SPF/DB) titanium structure for future Supersonic Cruise Research (SCR) and military aircraft primary structure applications. Using the horizontal stabilizer of the T-38 aircraft as a baseline, the structure was redesigned to the existing criteria and loads, using SPF/DB titanium technology. The general concept of using a full-depth sandwich structure which is attached to a steel spindle, was retained.

Trade studies demonstrated that the optimum design should employ double-truss, sinewave core in the deepest section of the surface, making a transition to single-truss core in the thinner areas at the leading and trailing edges and at the tip. At the extreme thin edges of the surface, the single-truss core was changed to dot core to provide for gas passages during the SPF/DB process. The selected SPF/DB horizontal stabilizer design consisted of a one-piece SPF/DB sinewave truss core panel, a trunnion fitting, and reinforcing straps. The fitting and the straps were mechanically fastened to the SPF/DB panel.

The program has produced results which will improve the efficiency of all future SPF/DB titanium structure. These include the development of deep-core sandwich fabrication methods, improved analytical tools for truss core evaluation as well as establishment of advanced SPF/DB processing methods.

17. Key Words (Suggested by Author(s))

Titanium, Superplastic Forming, Diffusion Bonding, SPF/DB Structures, Supersonic Aircraft Structure

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